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THE INFLUENCE OF MANURE HANDLING SYSTEMS ON HEAT AND MOISTURE LOADS IN FREE-STALL DAIRY BARNS

University — Université

U OF ALTA

Degree for which thesis was presented — Grade pour lequel cette thèse fut présentée

M.Sc IN AG. ENG

Year this degree conferred — Année d'obtention de ce grade	Name of Supervisor — Nom du directeur de thèse
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THE INFLUENCE OF MANURE HANDLING SYSTEMS ON HEAT AND MOISTURE LOADS IN FREE-STALL DAIRY BARNS

by

TIMOTHY JOHN QUILLE

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

IN

DEPARTMENT OF AGRICULTURAL ENGINEERING

EDMONTON, ALBERTA

SPRING, 1985

THE UNIVERSITY OF ALBERTA

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ABSTRACT

Ventilated animal structures require heat and moisture removal rates consistent with barn heat and moisture production. Determination of these removal rates is contingent upon design animal heat production data from the literature. However, a review of estimates of dairy cow heat production reveals a bias in favour of data from one particular type of dairy housing, namely, tie-stall buildings. Many of today's dairy barns are free-stall units and the heat loads produced within such barns may be different to those produced in tie-stall facilities.

Design data available to Canadian farmers are based largely on studies undertaken in the United States in the 1950's. Therefore, recent developments in areas such as livestock house design, manure handling systems and trends toward a larger animal group size are not reflected adequately in current ventilation design data. In particular, there is a complete absence of information on the influence of different manure handling systems on dairy barn heat and moisture production. Solid concrete passageways are popular in most free-stall designs. However, many dairy barn units utilize slatted passageways.

Accordingly, a study was initiated to determine the effects of the two manure handling systems on the heat and moisture loads in commercial free-stall barns. A data acquisition system capable of monitoring large commercial livestock facilities has been developed at the Department of

Agricultural Engineering, University of Alberta. This system was utilized in the monitoring of six free-stall dairy barns, three with scraped and three with slatted passageways, over continuous 48-hour periods. The measured heat and moisture production data were compared with North American and European design data.

Mean measured total heat loads compared closely with existing design data. Measured latent heat loads, ranging from a mean of 1758 kJ/(h.cow (500 kg)) for the barns with solid passageways to 1600 kJ/(h.cow (500 kg)) for the slatted units, greatly exceeded the existing design latent heat data at corresponding temperatures. The proportion of animal sensible heat converted to latent heat in evaporating moisture within the barns with solid and slatted passageways was estimated to be 28.7 and 25.0%, respectively. The ratio of latent to total heat in the exhaust air ranged from 0.34 to 0.47, the average for the six barns being almost 0.40.

Statistical analysis of the data revealed no statistically significant differences, at the five percent level, between the measured and existing design values for total heat production. The measured sensible heat data differed significantly, at the ten percent level, from the European sensible heat data. Analysis of the latent heat values yielded the greatest differences. The latent heat production measured in the solid passageway barns differed significantly at the ten percent level of significance, with the design values. The corresponding slatted passageway

data did agree statistically with the North American data.

Further statistical analysis involving the barn heat and moisture production data had all the barns been operated at the same temperature, was undertaken. The most significant difference was determined to be between the latent heat data, at the twenty percent level.

ACKNOWLEDGEMENTS

Funding for ths project was provided by Agriculture Canada. The cooperation of the six dairy producers, Ivan Jespersen, Ed Wedman, Ray Ohlmann, Henry West, Ed Boender and Harvey Volkman is appreciated. Also, the guidance of the project supervisor, Professor Brian McQuitty, and the assistance of Peter Clark and Dale Travis is appreciated. Finally, the advice of Professor Bob Hardin on statistical matters is acknowledged.

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1. Introduction

The relationship between man and animal, as suggested by Duncan (1983), has developed over the years from the symbiotic to the exploitative. Applying this contention to livestock production systems, there is a trend, more noticable in recent years, toward the large scale, total confinement of animals in an apparent attempt to increase efficiency, production and profits, possibly at the expense of animal welfare.

Domestication and intensive husbandry have altered profoundly the natural selection process. By providing animals with food and shelter and by restricting their freedom of movement, they are becoming increasingly dependent on the quality of the environment in which they are housed. However, experience over the past few years has shown that providing a well controlled environment is not sufficient for satisfying basic physiological and behavioural needs of domestic animals and that modern housing conditions for dairy herds have not always resulted in improvement of cattle health or production (Guss and Grout, 1973). Economic pressures of recent years have forced many dairy farmers into a program of confinement and intensification. A trend at variance with the traditional pasture scene has emerged which favours keeping animals on concrete throughout their productive lifetime. In addition, such labour-saving designs as slatted floors have helped to reduce drastically the space required per animal. These

trends were accepted rapidly in the absence of adequate data on the long-term effects of such confinement practices and conditions (U.S.D.A., 1964, cited by Albright and Alliston, 1971).

The risks of a gradual build-up of disease-causing pathogens within a livestock unit and the dangers of livestock groups becoming too large must be borne in mind. In all parts of the world where the development of large units has taken place, there have emerged viral diseases which tend to 'sweep' through areas with a high livestock population, leaving a trail of devastation that Sainsbury (1981) likened to a forest fire.

While some of these developments are probably undesirable from the point of view of animal welfare, the domestic animal has shown itself to be a very adaptive species. Beilharz (1982), as cited by Duncan (1983), emphasizes the evolutionary adaptation to the environment which accompanies, or is an integral part of, domestication, and points out that domestic animals are adapting continually to the intensive conditions imposed on them.

Production (milk, meat, eggs, hides and wool) and reproduction are the primary indices of the effects of stress, not only from an economic basis, but also as a composite of optimal physiological functions (Stott, 1981). While cow numbers steadily declined over the last three decades, production per cow increased from 2,404 kg/cow to more than 5,443 kg/cow between the years 1950 and 1981

(U.S.D.A. Agricultural Statistics, 1981, cited by Speicher and Hlubik, 1982). Agricultural Statistics (1972), cited by Bond (1976), reported a 100% increase in the liveweight of cattle and calves produced per cow during the period 1930 to 1970 in the United States. These increases resulted from expanding technology in the areas of animal genetics, animal breeding, nutrition, animal physiology and reproduction, disease and parasite control and, last but not least, environmental control within the livestock housing structure (Bond, 1976). In particular, the increasing use of versatile, reliable, modern digital electronic equipment is playing a significant role in the development of environmental control systems for all types of farm animal housing.

Modern agricultural research recognizes the interdependence of engineers, animal physiologists, veterinarians, and people from other disciplines. Agricultural engineers became involved in animal heat and moisture production research because of the importance of these parameters in the ventilation of livestock structures. The increasing cost of energy, coupled with the constant need for better animal welfare, have made the proper design and sizing of ventilation systems much more important. Minimum ventilation rates are based on a building moisture balance where latent heat gains must be equated by latent heat losses. Maximum ventilation rates are based on a building sensible heat balance where sensible heat

production must be equated by sensible heat losses.

The sensible heat and moisture production rates of confined animals are the main criteria in the design of ventilation rates. Early research into the determination of these data involved direct and indirect calorimetry. Even to the present day, the design of dairy barn ventilation rates for North American production facilities are based on studies concluded in the 1950's at the University of Missouri (Yeck and Stewart, 1959). These studies involved small numbers of cattle housed under conditions not unlike the stanchion barns of today. Turnbull (1973) reasoned that the moisture loads in free-stall barns, due to the large wet surface of passageways, probably would be greater than that indicated by the stanchion-tied cows on which the design data are based. This was confirmed by Smith et al. (1980) who found moisture loads to be significantly higher in two free-stall barns with scraped passageways than in two tie-stall operations.

Free-stall dairy units, however, utilize two different manure handling systems. One involves solid concrete passageways which are scraped regularly and the other slatted passageways with pits beneath in which manure is stored for several months. The influence of these manure handling systems on heat and moisture loads in free-stall units is unknown. The objectives, then, of this study may be summarized thus:

1. To establish the influence of manure handling systems on

heat and moisture production in commercial free-stall dairy barns.

2. To determine the total, sensible and latent heat production of confined dairy cows.
3. To provide design data for cattle ventilation and heat balance equations that are appropriate to today's dairy barn facilities.

2. The Animal Environment - A Literature Review

2.1 Introduction

The nature of an animal's life is shaped by environmental and hereditary forces. Curtis (1983) defined environment as the sum of all the physical, chemical and biological elements that surround the animal. Esmay (1977) described physical, social and thermal factors. A more general definition given by Ames and Ray (1983) describes the animal environment as any external factor that influences the productive response of farm animals. The animal thermal environment is determined primarily by the dry-bulb temperature, relative humidity and movement of the surrounding air. Consideration of the physiological base of cows' response to the thermal environment is warranted as this is a central topic to any discussion on dairy barn heat loads. This chapter also reviews dairy cow heat and moisture production research, and the relationship between these measurable quantities and ventilation system design are discussed.

2.2 Animal Physiology

2.2.1 Partition and Utilization of Dietary Energy

As illustrated schematically in Figure 2.1 after Young and Degen (1981), the gross energy intake of an animal minus fecal energy gives a measure of the apparently digested energy (DE) of the dietary energy. In the case of

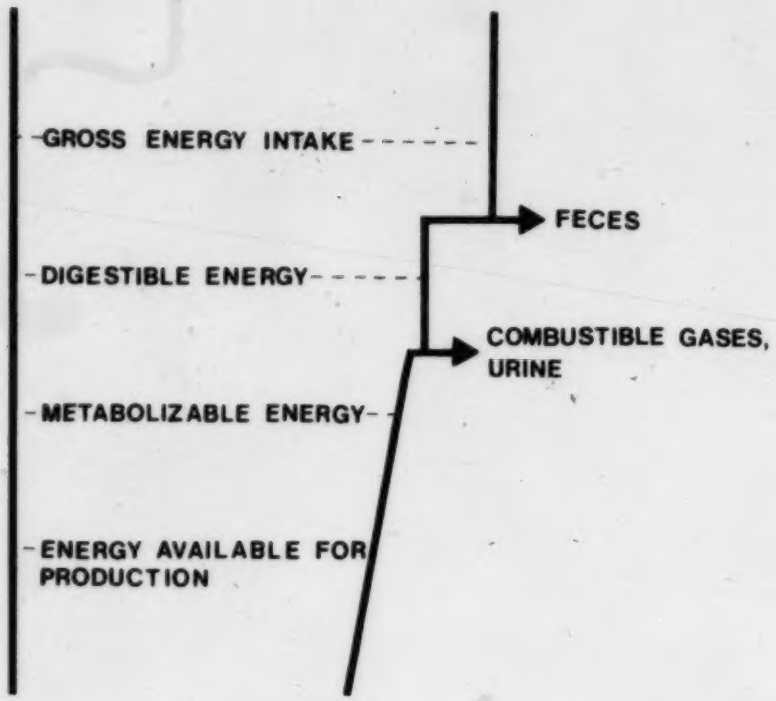


Figure 2.1 Scheme of an animal's dietary energy use.

ruminants, this fecal energy can represent up to 50% of gross energy (Curtis, 1983). DE, while depending primarily on the composition of the diet, is inversely proportional to the amount of feed-intake (Curtis, 1983). Subtracting the energy lost in the urine and that lost as heat and methane in the fermentation process in the gut from the DE, gives a measure of the energy available for maintenance and productive functions, that is, the metabolizable energy (ME). ME is typically 80-85% of the DE (Curtis, 1983). Energy surplus to maintenance needs is available for productive purposes. If the ME is insufficient for maintenance, the animal will make up the deficit by oxidation of its own body tissue (Robertshaw, 1981; Young, 1983).

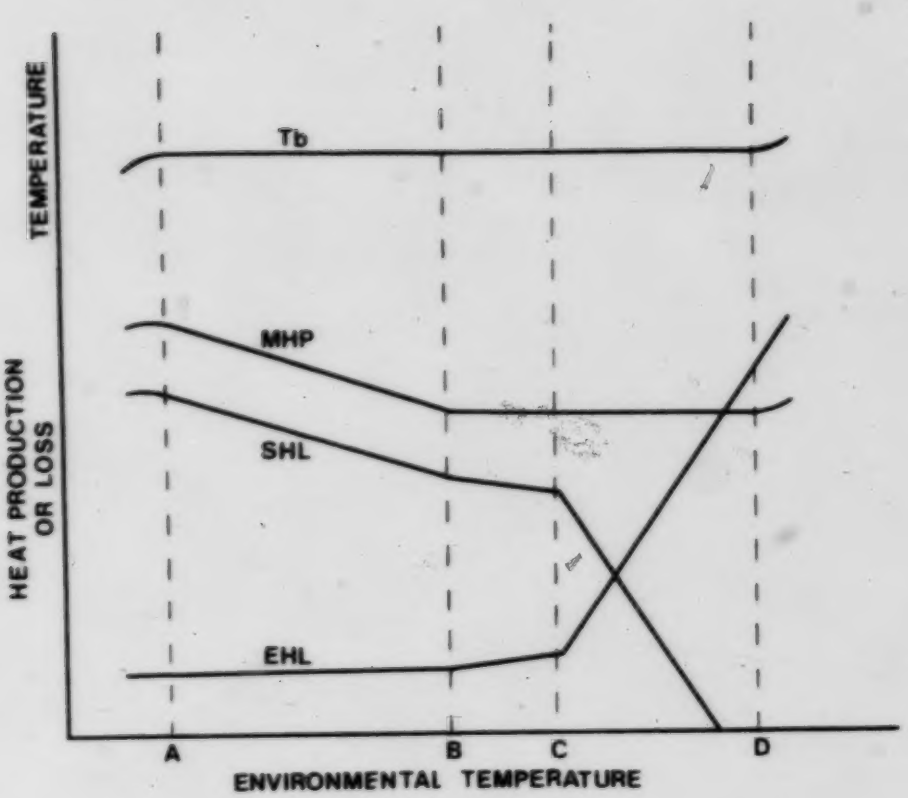
2.2.2 Animal Energy Balance

An animal is an open thermodynamic system, continuously trading energy and matter with its environment (Curtis, 1983). The energy budget equation for an animal links the chemical and mechanical energy gains with the rate of thermal exchange. The rate of chemical energy gain is the ME turnover. The rate of energy gain from the action of physical forces is the work rate, and has a negative sign in the usual case of an animal doing work against external forces. Together these constitute the metabolic work rate or the total rate of heat release within the body. The animal total heat loss subdivides into Newtonian non-evaporative or sensible heat transfer and evaporative

heat loss. Sensible heat transfer is by conduction, convection and radiation. For an animal of fixed mass and specific heat, the rate of heat storage is directly proportional to the rate of change of mean body temperature or the average temperature of the body tissue (Mitchell, 1977). Although at any particular instant the animal is likely to be storing or losing heat, the heat production and heat loss are in a dynamic equilibrium and the net rate of heat storage will tend to zero with time (Mitchell, 1974).

2.2.3 Thermal Zones

The basic concept of heat exchange between an animal and the thermal environment was illustrated in Figure 2.2 after Mount (1979). The rate of heat production or heat loss relies on the premise of a zone of thermoneutrality, represented by the temperature range BD, which ruminants have a marked ability to alter (Webster, 1981). Within this environmental temperature range, an animal's energetic efficiency is maximal, metabolic heat production is minimal, constant, and is independent of the ambient temperature (Curtis, 1982; Robertshaw, 1981). Also within this zone lies a small temperature range of minimal regulatory effort, which, for North American adult ruminants, is about 13 to 18°C (McDowell, 1974). Appleman and Owen (1970), cited by Albright and Alliston (1971), quoted a temperature range of -1.1 to 15.6°C as being the comfort zone for European breeds of cattle, whereas for East Indian breeds of cattle it was in the range of 10.0 to 26.7°C.



Tb = Deep-body Temperature
MHP = Metabolic Heat Production
SHL = Sensible Heat Loss
EHL = Evaporative Heat Loss

Figure 2.2 Thermal zones of mammals.

The lower border of the thermoneutral zone is called the lower critical temperature, LCT, that is, point B in Figure 2.2. This temperature describes the transition point between the thermal zone in which an animal maintains homeothermy by regulating heat loss and the zone in which homeothermy can be maintained only by regulating metabolic heat (Webster, 1974). Below the LCT, a point of summmit metabolism is reached, A, below which continued exposure to lower temperatures results in hypothermia (Young, 1983). The thermoneutral zone is bounded at the upper end by the upper critical temperature, UCT, that is, point D in Figure 2.2, beyond which further metabolic reduction cannot be used as a means for further reduction of body heat loss (Esmay, 1977). Albright and Alliston (1971) observed that the limits of thermoregulation of domestic animals were reached more quickly with increasing than with decreasing temperatures.

The principal factors that determine upper and lower critical temperatures include the metabolic heat production of an animal in its thermoneutral environment, the thermal insulation of the hair coat and the superficial tissue of the animal (Young, 1983; Christopherson, 1980). In addition, the full consequences of humidity, thermal radiation load, air movement, thermal adaption, plane of nutrition, breed and animal behaviour should be considered in using these temperatures (Young, 1983; Morrison, 1983).

In the course of developing equations to estimate the lower critical temperatures of dry and lactating cows, Hamada (1971) estimated lower critical temperatures for Japanese cows at maintenance and production of 10 and 20 kg fat-corrected milk daily to be 2, -4 and -10°C, respectively. Young (1981) estimated typical LCT values for dry pregnant beef cows during Canadian winters to range between -10 and -20°C, while for high producing dairy cows and feedlot beef cattle, figures below -20°C are quoted. Curtis (1983) notes that LCT values may fall below -40°C in older cattle on full feed. In summary, cold-adapted adult ruminants on full feed and with substantial thermal insulation are very cold-hardy and have generally a very low LCT. In the dry, cold, agricultural regions, these animals rarely experience direct cold stress, (Webster, 1974).

With respect to UCT values, Ragsdale et al. (1949), cited by Morrison (1983), reported marked decreases in feed intake and milk production above 25°C in cattle calorimetric studies. Fuquay (1981) reported that UCT values between 24 and 27°C have been established for a number of production traits in mature cattle.

2.2.4 Heat Production

Animals produce heat through the maintenance of essential body processes, through physical activity and through digestion. The primary basal body functions involve action of the organs such as the heart, lung, and liver. Physical activity varies with such parameters as ambient

temperature, management practices and housing type. For example, ruminants fed in a barn require 40-70% less energy expenditure than feeding by conventional grazing (McDowell, 1974). Heat of digestion is due to the many processes associated with maintenance of living cells and tissues. These processes include movement of the alimentary tract, chemical processes of digestion, rumen microflora and absorption of digestive products from the alimentary canal (McDowell, 1974). Wiersma (1976) reported that heat of digestion is particularly high in heavily-lactating animals.

The heat generated through ingestion of feed varies with the class of nutrient ingested and is highest in protein (Wiersma, 1976). However, the metabolism of protein is independent of environmental temperature and the increase in ruminant heat production in the cold is due to an increase in the catabolism of fat (Blaxter and Wainman, 1961, cited by Thompson, (1973). In ruminants, the micro-organisms contained in the rumen constitute an extra source of heat, contributing up to 10% of an animal's basal heat production (Wiersma, 1976). This heat gain, however, may be neutralized by the ingestion of cold material, as identified by ASHRAE (1981).

Biochemical and physiological reactions occur at rates determined partly by temperature. The amount of animal heat produced at thermoneutrality increases with increase in bodyweight. The production rate is expressed usually per unit of surface area (m^2) or per unit of body weight (kg)

raised to the power of 0.75 (Klieber, 1961). The rate of metabolic heat production in a thermoneutral environment ranges from about 50 to 200 W/m² depending on species, bodyweight, level of feeding and the productivity of the animal (McArthur, 1981; Thompson, 1973). Below the LCT, cattle produce approximately 2.4 W/m² more heat for each 1°C fall in environmental temperature (Mount, 1979). The metabolic rate can reach 500 W/m² in response to summit metabolism, but this level cannot be maintained for more than a few hours.

For optimal efficiency, regarded as a condition that favours survival in the evolutionary sense, heat production should be maintained at the minimal economic level required for the maintenance of body processes (McLean, 1973). In practice, heat production is determined largely by the level of food intake, which, for farm animals, is related to optimal productive efficiency rather than to environmental warmth. As heat production is achieved by the oxidation of food intake or body reserve (for example fat), an increase in metabolic rate above the normal rate results in lowered productivity. This is due to a higher proportion of the food eaten being employed in thermoregulation. Indeed if metabolic rate exceeds the rate of supply of metabolizable energy (as feed intake), then body mass will decrease (McArthur, 1981).

Heat production or thermogenesis is regulated by mechanisms such as shivering, changes in muscle tonus, and

secretion from endocrine glands, which increase the metabolic heat production (Esmay, 1977). These adjustments are made through the afferent and effector paths of the central nervous system.

2.2.5 Heat Loss

The animal heat balance is maintained to some extent by control of heat production but, for the most part, it is attained by regulation of heat loss (Aschoff et al., 1974), a predominance that is most evident within the zone of thermoneutrality. The capacity of an animal to produce heat in cold environments and its reserves of heat and chemical energy are related closely to body mass. Heat loss from animals, on the other hand, is related to surface area. The smaller an animal, the greater its surface area to mass ratio, and, therefore, it is more susceptible to excessive heat loss and exhaustion of its energy reserves (Young, 1981).

Control over skin blood flow is the principal physiological mechanism for regulating body temperature (Hey, 1973). This heat transfer from the central core to the surface is controlled primarily by vasoconstriction to reduce blood flow in the presence of cold and or by vasodilation to increase blood flow in the presence of heat. Vasodilation is highest in body parts which have a high surface to volume ratio such as the ears, the legs, and the tongue (Wiersma, 1976).

The overall thermal insulaton of an animal is the sum of the insulation of the tissues, the insulation of the hair coat, and the insulation of the coat surface-air interface. At the skin surface, increased insulation is effected by piloerection to increase the depth of the hair coat and reduce the loss of sensible heat. The thermal resistance of the hair coat depends almost entirely on the entrapped air which occupies over 95% of the volume of the hair coat. Seasonal or long-term changes are effected by increased hair production or by shedding (Wiersma, 1976). At environmental temperatures below the LCT, when vasoconstriction and piloerection are maximal, the overall insulation, measured by indirect calorimetry, is 0.42 $m^2°K/W$, (Thompson, 1973). This figure falls to 0.33 $m^2°K/W$ in the absence of vasoconstriction and piloerection.

The heat generated by metabolism is carried to the skin surface by conduction across the tissues and particularly by convection in the circulatory system (Wiersma, 1976). At the skin surface, some of this heat energy is used to evaporate water which is lost to the environment. The remainder is lost by conduction across the hair coat and the boundary layer of still air, by convection from the boundary layer to freely moving surrounding air, and by radiation, chiefly from the tips of the hair across the boundary layer (Wiersma, 1976).

2.2.6 Sensible Heat Losses

2.2.6.1 Conduction

Conductive heat exchange between the animal and the environment occurs mainly through direct contact with another surface (for example, a stall floor) that is at a higher or lower temperature. From Equation 2.1, the rate of conductive heat transfer depends on the temperature differential, the area of contact and the conductivity of the contacting surface.

$$QC = k\ A\ (t_1 - t_2) \qquad \text{Eqn. 2.1}$$

where QC = conductive heat transfer, Watts

k = thermal conductivity of environmental substance, Watts/(m^2°K)

A = animal's effective conductive surface, m^2, and

$t_1 - t_2$ = difference between the temperature of the environmental substance at a point some distance from the animal and at the point of contact with the animal, °C

Therefore, with regard to animal housing, conduction is of significance only when an animal is lying down. Mahoney et al. (1969) estimated this to be 55% of the time for their test cattle. In a similar experiment, Hahn et al. (1969) found a figure of 45 to 50% for Holstein cows.

2.2.6.2 Convection

Convective heat exchange with the environment is the transfer of heat energy between the surface of an animal and the air moving around it. Equation 2.2 describes this heat loss or gain.

$$QV = h\ A\ (t_1 - t_2) \qquad \text{Eqn. 2.2}$$

where QV = convective heat transfer, Watts

h = heat transfer coefficient, Watts/(m^2°K)

A = animal surface area effective in convection m^2, and

$t_1 - t_2$ = difference between the animal's surface temperature and the environmental air temperature, °C

The convection coefficient, h, depends on the air velocity and other physical factors such as thermal conductivities and thicknesses of the animal's cover and boundary layer. The convection coefficient can be found experimentally by use of the dimensionless parameters - the Nusselt Number, the Reynolds Number, the Prandtl Number and the Grashof Number.

Kibler and Brody (1954), cited by Thompson (1973), showed that winds of 3.6 m/s increased the sensible heat loss of cows by about one third. Thompson et al. (1954), cited by Wiersma (1976), observed that increasing air velocity reduced skin and hair temperature roughly in

proportion to the decline in ambient temperature. When there is no induced air movement over an animal's surface, there is no forced convective heat transfer but only free convective heat transfer (Mitchell, 1974). The circulation of air around the animal is then determined by its buoyancy and, therefore, by a gradient of air density (Monteith, 1973). Forced convective transfer also may take place in the respiratory tract of animals. However, respiratory convection is a minor avenue of heat exchange when compared with respiratory evaporation (Mitchell, 1974).

2.2.6.3 Radiation

Radiation exchange between two surfaces involves absorbance, emission and reflection. The net rate of transfer of radiant heat between an animal and its environment may be given by:

$$QR = \sigma A F j (T_1^4 - T_2^4) \qquad \text{Eqn. 2.3}$$

where QR = rate of radiation heat transfer, Watts

σ = Stefan-Boltzmann constant, Watts/($m^2 °K^4$)

A = surface areaof one surface, m^2

F = shape factor

j = dimensionless factor to account for the emission and absorption characteristics of the two surfaces

T_1 = average absolute temperature of animal's radiant environment, °K, and

T_s = average absolute temperature of animal's radiant surface, °K

The radiant heat which participates in the energy budget of animals covers a wavelength range of about 0.3-100 μm (Cena, 1973). Based on a difference in the optical properties of animal coats, the spectrum is divided into shortwave (wavelength < 2-3 μm) and longwave regions (wavelength > 2-3 μm). Radiation absorbed and emitted from the animal itself falls entirely into the latter region as does the radiation from the ground, vegetation or indoor enclosures (Mitchell, 1974). The contribution of solar radiation to the energy balance for a structure should be taken into account in the determination of heat flows through the various components of the building. Shortwave radiation is generated by the sun and, therefore, has little effect on the energy balance of animals in confinement livestock buildings. This is particularly true of the northern latitudes of Western Canada.

2.2.7 Evaporative Heat Losses

Sensible heat losses are by and large proportional to the difference in temperature between an animal and its surroundings. Therefore, as ambient temperature approaches body temperature, heat losses by conduction, convection and radiation become smaller and the proportion of heat lost by evaporation becomes larger.

Water for evaporative cooling may originate from the sweat glands, from the membranes of the respiratory tract

and from diffusion across the skin. The relative contribution made to the total evaporation by cutaneous and respiratory evaporation varies with species. Thompson (1973) estimated that, for cattle in an environment of 15°C, 46% of the total evaporative heat loss is from the skin, the remainder being due to respiration. As the temperature increases, that fraction lost from the skin increases more rapidly. Kibler and Brody (1954), cited by Thompson (1973), observed a noticable increase in cutaneous evaporative heat loss above 18°C.

Equation 2.4 describes how a humidity difference provides the potential for cutaneous evaporation:

$$QE = e\ A\ (p_1 - p_2) \qquad \text{Eqn. 2.4}$$

where QE = evaporative heat loss, kg/s

e = evaporative diffusion constant, kg/s N

A = effective animal wetted area, m^2, and

$p_1 - p_2$ = vapour pressure of the skin surface minus that of the air, N/m^2

The factor e, above, takes into consideration the air velocity.

At high environmental temperatures, when temperature gradients are limiting factors in an animal's heat budget, cattle rely almost solely on evaporation of water to dissipate excess heat, either from the skin surface as a result of sweating (though they are classed as nonsweating

animals) or the respiratory system by panting. Whereas ambient air humidity affects panting, respiratory ventilation is the controlling physiological parameter (McLean, 1973). Panting is not as effective as sweating as a heat dissipation mechanism at high temperatues, and in addition, there is the possibility that the effort of panting increases the cow's heat production (Thompson, 1973).

2.2.8 Physiological Control Systems

Adaption by livestock to intensive housing conditions involves behavioural and neuroendocrine adjustments aimed at decreasing the adverse effects of environmental stimuli (Dantzer et al., 1983). To this end, conventional, negative feedback control loops are becoming an increasingly common approach to describe this dynamic homeostasis. In spite of wide variations in environmental, nutritional, or pathological conditions, the animal is able to control blood pressure and composition, body temperature, respiration, cardiac output and many other such variables, without conscious effort (ASHRAE, 1981). The apparent ease with which this consistency is achieved disguises the efficiency and the complexity of the mechanisms involved (Hey, 1973).

One stable physiological control system of importance to the agricultural engineer is the homeothermic closed loop system (Figure 2.3). This system allows an animal to adapt to its thermal environment by adjusting both internal heat production (metabolic heat) and heat loss mechanisms

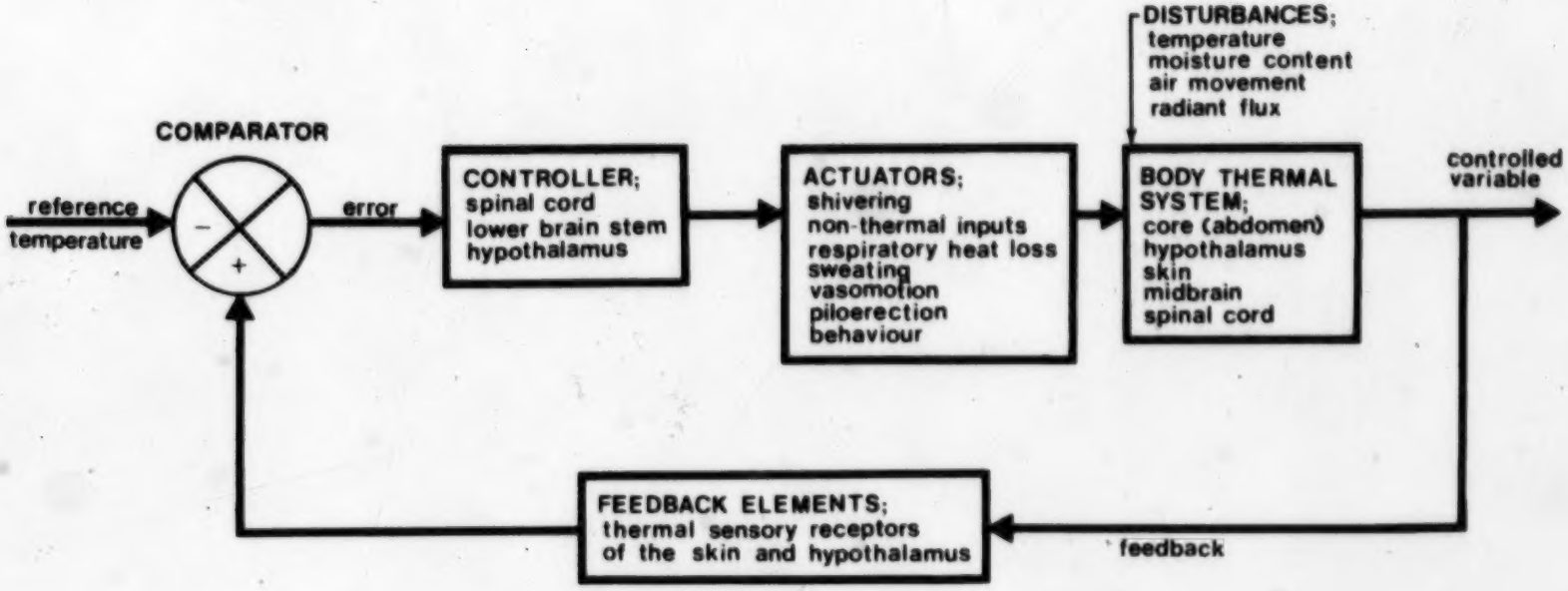


Figure 2.3 Control system analogy of a temperature regulating system for homeotherms.

(respiratory heat loss, sweating, piloerection and behavioural responses) (Scott et al., 1984). The result is regulation of deep-body temperature.

The temperature regulating system consists of three basic components; sensors, a thermostatic control unit, and thermoregulatory effectors (Wiersma, 1976). The body itself is the control system which can be subjected to a disturbance, usually in the form of environmental heat, cold, or internal heat, as in exercise and fever. Thermal sensory receptors, both warm and cold, are located in the skin and in the central core of animals. By way of the afferent neural system, these sensors detect the disturbances, and transduce them into neural signals, thus providing continuous information to the animal's central nervous system about its thermal state (Dantzer et al., 1983; Young, 1981). The neural information enters the central nervous system and is focused on the hypothalamus. This organ links the neural and the endocrine systems (Curtis, 1983). Here the deviation of the controlled variable from the reference value constitutes an error signal which activates a central controller. This, in turn, elicits a thermoregulatory actuator in the form of an efferent neural signal that is related to prior thermal exposure, the rate of thermogenic processes and the net heat exchange with the environment (Elizondo, 1977; Young, 1981). The precise nature of the controlled variable remains undefined but probably is a combination of central nervous

system, peripheral and deep body temperature (Mitchell, 1974; Elizondo, 1977). In any event, the animal responds physiologically to imbalances between rate of heat production and heat loss caused by changes in the thermal environment (Scott et al., 1984). This response involves the hormonal state changes in the animal or specific animal behaviour. Thus, the processed sensory information counteracts the disturbance, tending to return the controlled variable toward its reference point. This point is a deep body temperature of approximately 38 to 39°C in dairy cattle (Hales, 1974; Keener et al., 1973).

The complexity and numerous theories of thermoregulation cannot be covered adequately in detail. For example, Thompson (1973) observed that surface thermoreceptors dominate over deep body ones since the former provide anticipatory capabilities to set the control mechanisms in gear before ambient temperature changes affect the core temperature. This could imply a feedforward control system for animal physiological thermoregulatory responses. In any event, Figure 2.3 represents general characteristics of the temperature regulation system in domestic farm animals.

2.3 Environmental Stress

The objective of dairymen should be to increase the productive life of the dairy cow. One way to promote this is to ensure cow comfort by providing a stress-free

environment (Albright, 1983). A decline in milk production and disease resistance, which occur in direct relation to the degree of stress imposed, are two typical symptoms of environmental stress (Guss and Grout, 1973). Aside from these, rate of gain or growth, efficiency of feed utilization, body and skin temperature, respiration rate, metabolic rate and other such indices are commonly used to relate cow comfort to production (Wiersma and Stott, 1968).

Thermal comfort is the principal criterion to be satisfied in providing a stress-free environment. Albright (1983) noted that cows are considerably more sensitive to high than to low temperatures. The primary cause of heat stress is high air temperature combined with high humidity. In addition, high elevated skin temperatures, high respiratory rates and the associated thermal discomfort reduce an animal's appetite and, therefore, lower its productivity (McArthur, 1981).

Due to the length and severity of some Prairie winters, cold stress is a more relevant concern to Western Canadian farmers than is heat stress. The metabolic response to the stimulus of cold involves practically all the systems in the body. Blood vessels dilate in shivering muscles, cardiac muscle beats faster, respiration becomes deeper and the urine flow is increased (Webster, 1974).

With regard to the dairy cow, cold stress may be considered not as a systematic but a local problem (Webster, 1981). While MacDonald and Bell (1958) showed that milk

production of dairy cows falls at an ambient temperature below about 0°C, milk synthesis depends on blood flow to the mammary gland, and this is reduced by local cooling (Thompson, 1977). In order to determine the impact of local cooling, Holmes (1971), cited by Stewart (1976), covered one half of the udder of two Jersey cows and cooled the other half by an increase in air movement at an air temperature of 6 to 10°C. The combined effect was estimated to cause a cooling equivalent to an air temperature of -10°C. After 22 hours of cooling, Holmes (1971) found that yields of milk, fat, protein and lactose were reduced significantly. Thus, direct chilling of the udder depends as much on the thermal properties of the floor as on the ambient temperature (Webster, 1981).

The major effect of cold is not as the direct consequence of an animal's need to produce heat to maintain homeothermy, but rather the prolonged effect of cold reducing the efficiency of digestion and increasing the animal's maintenance requirements, (Young and Degen, 1981). This reduction in digestive efficiency occurs most noticably with roughage feeds (Young, 1981).

The ability of animals to cope with cold improves during exposure to mildly cold conditions. The adaptation involves increases in thermal insulation, appetite and basal metabolic intensity (Young and Degen, 1981), that improve the cold hardiness and reduce the risk of both acute and chronic cold stress. Chronic exposure, whether it be to

heat or cold, results in acclimatization (Folk, 1974).

Physical comfort, disease control and behavioural satisfaction are other criteria that Webster (1983) defined as requirements that need to be satisfied in a stress-free environment. However, management methods based on cost per man-hour rather than optimal productive efficiency of animals often dictate practices. Accessibility of feed may be more important to animals than the actual amount present. Holstein cows fenceline fed a complete ration of silage and concentrates, ate 26% more of the time than the same size group eating from a smaller bunk (Albright, 1983), thereby increasing their thermoneutral metabolic rate.

2.4 Summary of Animal Physiology

Many factors control or influence the heat and moisture production of dairy livestock. A basis for analysis is provided by the animal energy balance equation. The temperature of a homeothermic animal's body is essentially constant. This condition depends on the equilibrium among the amounts of heat the animal produces metabolically, energy gains from the environment, and energy losses to the environment. While heat production is determined primarily by the level of food intake, heat loss is primarily a function of the animal environment. Heat exchange with the environment is accomplished by three modes of energy transfer, conduction, convection and radiation. Temperature gradients provide the basis for these sensible heat flows.

Animals also lose heat by evaporation of water from the respiratory tract and skin surfaces. This latent form of heat flow occurs primarily along a vapour pressure gradient.

An animal employs complex thermoregulatory mechanisms in order to overcome adverse environmental conditions. In most circumstances, both behavioural and physiological responses are involved. In overcoming some of the more stressful impositions of livestock confinement conditions on the Prairies, animal responses often result in increased maintenance requirements and reduced productivity. Emphasis will now move from individual animal physiology to the animal accomodation and the indoor environment. In the following sections the influence of confinement housing on dairy cows and the environmental modifications required as a result of those influences are discussed.

2.5 Dairy Building Heat and Moisture Research

2.5.1 Dairy Livestock Housing Design

Over the last two or three decades, a trend toward fewer, larger and more highly mechanized dairy housing facilities has developed. As the costs of housing, milking equipment and manure handling facilities escalate, dairy producers need to attain a higher output per cow and man. The type of housing will affect costs of labour and feed, operator and cow comfort, animal health, cleanliness and sanitation levels and possibly milk output (Albright and Alliston, 1971). In addition, Turnbull (1973) pointed out

that the amount of barn latent heat produced would vary for different barn designs.

Dairymen in Canada utilize two general housing types. In the first design, the cows are confined by stanchions or tie-stalls on a lightly-bedded, hard-surface floor. The other design utilizes a pen or loose-housing arrangement which permits freedom of movement except during milking (Albright and Alliston, 1971). The fact that the former type of barn is labour intensive in milking, feeding and in manure handling has been, and will continue to be, an important reason for dairy farmers with larger herds to consider loose-housing systems (Speicher and Hlubik, 1982).

In the early loose-housing systems, large amounts of bedding were placed uniformly on an even concrete floor. The free-stall concept developed in the late 1950's and was taken up quickly (McQuitty, 1984), resulting in many of the older loose housing units being converted by incorporating free-stalls. The conventional loose housing was regarded generally as being more disease-predisposing than tie-stalls. Also, many incidences of trampled teats occurred in these early loose-housing designs. The spread of free-stalls, however, resulted immediately in cleaner cows, and fewer cases of udder injury (Speicher and Hlubik, 1982). Williams (1973) estimated that free-stalls reduce the amount of bedding required in the older loose-housing systems by about 75%. Less bedding results in less waste to be removed. Also, liquid manure disposal is more feasible

from the point of view of labour and handling.

There are some disadvantages with free-stalls. Feet, leg and pelvic injuries, however minor, are frequent occurences. While the dairyman may be offered the opportunity to extend his management capabilities over a large number of animals, individual animal attention may be sacrificed somewhat as when compared, for example, to a tie-stall unit operation.

Stall bases or floors are usually of two types, concrete or clay. Of the two, clay is preferred as a base for stalls due to its absorption qualities and being less stressful on the resting dairy cows. Almost without exception, some kind of bedding material is used on all commonly-used stall bases. Depending on the type of manure handling system employed in a barn, a particular type of bedding may be desired and even required.

Free-stall systems have dominated recently new barn installations. Pohl (1984) estimated that free-stall units constitute 35% of all barns in Alberta. Tie-stall barns account for 45%, with the other loose housing systems making up the remainder of the dairy barns. Free-stall systems provide flexibility in handling the dairy herd, reduce physical injuries to cows, and work well with a milking parlour.

2.5.2 Manure Handling Systems

A planned manure handling and disposal system is an important component of a dairy operation. Manure collection, transport, storage and land application must be compatible with sanitary milk production. In addition, minimizing odours, controlling flies and other nuisances, and guaranteeing the safety of people and animals are also primary considerations (Midwest Plan Service, 1976).

With the advent of free-stall housing systems, new approaches to manure handling were developed that would be compatible with the changing housing designs (Speicher and Hlubik, 1982). The two most common forms of manure handling in such housing are tractor-mounted or mechanical scrapers and slatted floors. Concrete passageways should be scraped at least once a day. Slatted passageways eliminate the scraping chore and cost of scraping equipment as manure passes through the slats into storage beneath before removal in liquid form after several months.

The moisture evaporation from a barn floor may be large in heavily-populated buildings with solid impervious floors. Therefore, the fraction of sensible heat used to vaporize water may vary with management practices. Since the total heat production is not significantly affected by the type of floor surface (Hinkle and Stombaugh, 1984), the ratio of sensible to latent heat may change with the type of manure management system used. The latent heat to be removed from a building also may increase (with a corresponding decrease

in sensible heat) because of floor flushings, water wastage and less frequent scraping of solid floors. Slatted floors, with pits underneath, allow a larger portion of the animals' liquid waste to be removed quickly from the animal area. Thus, less of the animal sensible heat production is used to vapourize floor moisture.

2.5.3 Animal Heat Production Research

Historically, agricultural engineers have looked to animal physiologists and nutritionists for design data on animal heat and moisture production (Stewart, 1976). These data were obtained by two commonly-used techniques which relied on direct measurement of heat loss from an animal or on its estimation from the quantitive collection and analysis of the gases involved in the oxidation of substrate used to provide the animal with energy (Farrell, 1974). However, inherent in direct and indirect calorimetry are a number of assumptions. In commercial cattle production, the animals are subjected to a range of environmental influences not encountered during calorimetric measurements. These include factors such as fluctuations in social structure and climatic environments as well as variations in nutrition and management practices. For this reason, data obtained from calorimetric observations should not be extrapolated without some further experimentation to the field situation (Farrell, 1974). In addition, Stewart (1976) noted that the research of physiologists was aimed directly at an increase in basic understanding of thermoregulation, and that its

application to housing research was indirect.

Bates (1974) recognized that environmental control systems used in present livestock structures have been developed primarily on an empirical basis from design information based on experiments involving individual animals or small groups housed in the manner of a conventional tie-stall barn. As was pointed out previously, free-stall barns have become more and more prevalent in recent years, replacing loose housing and, to a lesser extent, tie-stalls in the process. Within these structures, large groups of animals are housed in a manner in which individual animal activity and behaviour may be appreciably different to that of animals under experimental observation. In addition, today's solid passageway systems present large evaporative surfaces which add to the moisture load on the ventilation system (Bates, 1974). Slatted-passageway, free-stall barns present a different evaporative surface to those with solid passages. In summary, consideration should be given to the constraints under which research data are collected before applying the results to field problems.

A milestone in the development of knowledge of environmental control for dairy barn structures was the dedication in 1948 of the Psychroenergetic Laboratory at the University of Missouri. This environmentally-controlled test facility comprised two 5.5 by 7.9-m rooms housed within a rigid framed structure. Each room had a capacity of six mature cattle in stanchions. The ventilating air was

cooled, heated, dehydrated or humidified as required. Of the many tests carried out in the laboratory between 1948 and 1959, 12 were concerned with the effects of temperature, humidity, air velocity and thermal radiation on mature cattle.

Yeck and Stewart (1959) published a summary of the dairy cattle research based in this laboratory. This included reference to 51 research bulletins published by the investigators in the first ten years of research. Early researchers included S. Brody, H. Thompson, R. Yeck, L. Hahn, M. Esmay, R. Stewart and M. Shanklin. The researchers produced, in graphical form, 'barn' heat and moisture production rates with respect to temperature. Heat production per unit body weight decreased with environmental temperature while barn moisture, on the other hand, increased. The vapourization of water directly from animals, expressed as a percentage of total animal heat production, increased slowly from 10% at -18°C to about 25% at 10°C. Thereafter, the rate increased at a sharply increasing rate until it was about 100% at 38°C. As much as 80% of animal latent heat losses occurred from the outer body surface at high temperatures. Animal latent heat accounted for 55 to 60% of the total barn latent heat load at environmental temperatures up to 10°C. Beyond 10°C, the percentage of latent heat from the animal increased markedly. In tests of diurnally variable temperature conditions, the researchers observed that a diurnal cycle

was roughly comparable to a constant temperature exposure, equivalent to the average temperature of the diurnal cycle.

Two Danish researchers, Strom and Feenstra (1980) conducted an extensive review of existing heat and moisture data for dairy cattle. The authors developed rigorous heat loss equations based on the heat losses from maintenance, pregnancy and milk production. In their literature review, the authors selected data only from experiments that satisfied a number of criteria, namely, the indoor climate and the time of acclimatizing, the duration of the experiments, the breed of the animals and the level of production, feeding and bedding. For example, primary sources of information were experiments in which the livestock were subjected previously to thermoneutral conditions and were of a breed and had a level of production corresponding to intensive animal husbandry as existed in Denmark.

Strom and Feenstra (1980) noted that most of the heat loss data from animals are found as by-products from feeding experiments, hence the need for the above requirements. With specific reference to cows, the authors found a substantial amount of research had been conducted on the heat loss associated with milk production. However, few data from experiments were available for the maintenance heat loss and for the addition for pregnancy for cows.

Since the source reference material gave total heat losses at different temperatures, Strom and Feenstra

corrected this imbalance by calculating the ratio of the total heat loss measured at the particular experimental temperature to the total heat loss at 20°C. A temperature correction factor, therefore, was calculated for each class of animal.

The authors emphasized that the experimental data used in the formulation of the heat loss equations were gathered under, as near as possible, commercial conditions. With regard to the influence of floor type on barn heat loads, no experimental data were found that distinguished between solid and slatted floors.

Strom and Feenstra compared their data with those published in the ASAE Yearbook (1979), which, were derived from Yeck and Stewart (1959). For dairy cows, the Danish total heat production values were a little higher than the corresponding ASAE values. The main reason for this discrepancy was the high correlation with milk production of the Danish values. In addition, Strom and Feenstra were critical of the short measurement periods of the American experiments and the exclusion of the effects of normal housing activities in the total heat production values.

Of the few cattle environmental research experiments performed under actual production conditions, Remmele et al. (1973) examined heat and moisture production from a slatted-floor beef unit. The experimental procedure involved continuous monitoring over a 2-month period of 47 penned Hereford steers averaging 240 to 290 kg. Of

particular interest to the researchers was the heat and moisture contributions to the environment from the manure storage tank located under the slatted floor. Relative humidity and animal density accounted for 33.8% of the variation in building latent heat production, which, included the manure storage tank heat contributions. The inlet dry-bulb temperature accounted for 30.9% of the same variation. The inverse relationship between inlet air temperature and sensible heat production accounted for 66.6% of the variation in barn sensible heat output, with increases in relative humidity tending to increase the heat production values. The authors concluded that the overall effect of the manure storage tank was to remove approximately 185 kJ/(h.head) of sensible heat from the animal environment while adding 216 kJ/(h.head) of latent heat.

Cargill and Stewart (1966) examined the effect of temperature and humidity on total heat and vapour dissipation of lactating Holstein cows. The experiment was undertaken at the climatic laboratory at the University of Missouri which was described previously. Two test groups of six cows each were subjected alternately to control and experimental conditions. Two temperatures, 26 and 32°C, and three humidities, high, medium and low, all within limits of 20 and 80% relative humidity, were used for the experimental conditions. Total heat and total vapour dissipation, including that from wet surfaces, were found to decrease

with increased relative humidity. In addition, total heat was found to decrease at high temperatures while total vapour increased.

Shanklin and Stewart (1966) used a different approach in their study of environmental effects on animal production by examining the animal's surface temperature, since this parameter is of prime importance in the heat transfer between an animal and its surroundings. The tests were undertaken on 12 lactating Holstein cows at the University of Missouri climatic laboratory. Due to the effect of stage of lactation on the physiological responses of stressed animals, the researchers divided the cows into early, middle and late lactation. To facilitate the separation of the effect of normal decline in lactation from any environmental-imposed effects, the previously described switchback design was employed. Experimental conditions consisted of humidities of 30, 50 and 80% at 26°C and 20, 40 and 50% at 32°C, aside from the reference conditions of 18°C and 50% relative humidity.

In a statistical analysis involving temperature, humidity, stage of lactation and growth, the authors found that there was no significant effect of either stage of lactation or growth on surface temperature. However, at the two environmental temperatures under observation, the skin-hair temperature difference increased from low to medium humidity, and decreased from medium to high humidity, the reference condition following identical patterns.

Despite the fact that no decrease in metabolic rate was recorded, the authors explained this phenomenon of surface temperature decrease at the highest humidities in terms of blood circulation. They proposed that in 'non-sweating' species at high environmental temperatures, increasing humidity decreases surface vapourization potential which is associated with a pooling of blood in the body interior. As expected, the absolute values of the surface temperatures measured at 32°C were higher than those measured at 26°C which were, in turn, higher than those measured at the reference temperature.

As pointed out by Strom and Feenstra (1980), a considerable amount of 'cattle heat of production' data exists as compared with heat data due to the other main sources, such as maintenance heat and heat production due to pregnancy. Berry et al. (1961) compiled a summary of the experiments carried out at the psychroenergetic laboratory in Missouri up to 1961 on the effects of temperature and humidity on milk production. Holsteins were used predominantly in these studies and were the sole contributors to this summary. The normal level of milk production was assumed by the authors to be that produced between 10 and 18°C and, despite the variation in management and feeding levels during the several studies, certain practices regarding these parameters were followed consistently, thus lending some uniformity to the review. In their conclusions, Berry et al. (1961) found that both

temperature and humidity began to affect milk production only at temperatures higher than 25.4°C, the effect of humidity increasing as the dry-bulb temperature increased. The authors went on to produce graphically estimates of percent of normal production as a function of known air temperature and wet-bulb temperature.

Smith et al. (1980) compared the heat and moisture production of two tie-stall and two free-stall facilities. The moisture production in the free-stall barns was significantly higher, at comparable ambient temperatures, than in the tie-stall facilities. Smith et al. (1980) also concluded that all heat production parameters exhibited more variation that was predicted by the existing design values.

One of the most influential building parameters in the determination of animal heat production data is the floor type. The effect of a solid as opposed to that of a slatted floor on ventilation loads has received little attention from livestock heat and moisture production researchers. With regard to dairy cattle structures, very little research has been forthcoming, as was evident from the extensive review conducted by Strom and Feenstra (1980). Feddes and McQuitty (1973) investigated the influence of fully slatted and straw-bedded beef housing systems on building moisture loads. The ratio of water vapour removal rate for the slatted and straw-bedded housing systems was determined to be 0.69. This result was arrived at when there no agitation of the liquid wastes in the slatted-floor housing system as

aeration rotor operation was found to cause a significant increase in moisture removal rates.

Some relevant work has been done on the effect of floor type on swine housing moisture loads. Harman et al. (1968) found that ventilation rates for a slatted-floor swine finishing house can be reduced below that required to prevent condensation in a similar concrete-floor house as a result of the reduction in moisture evaporation from the former. In a study of commercial swine barns, Clark et al. (1980) found a 4 to 5% greater conversion of sensible heat to latent heat in solid floor passageways than in those with slatted-floor passageways.

2.6 Environmental Control Systems

2.6.1 Introduction

The heat dissipated by an animal is ordinarily useless to the animal after this heat passes to the environment unless the animal's microenvironment is warmed (Curtis, 1983). Therefore, responsibility lies with the ventilation system designer to make maximum use of this energy source. In previous sections, the heat balance of individual animals was examined. This section looks at the heat balance of an animal livestock barn. Similar physical processes to the animal heat balance are involved. Metabolic heat from the animals and, in some cases, forms of supplemental heat are added to the barn air. This heat is lost primarily due to air movement through the house and also by conduction

through the building fabric.

2.6.2 Ventilation System Design

The design of functional ventilation systems for dairy barn applications involves the integration of a number of factors. These include the principles involving air flow, physiological responses of dairy livestock, ventilation system control and management and economic considerations. Ventilation systems are of two types, natural or mechanical. The former depends on natural forces to produce a pressure differential necessary to cause air flow. Therefore, ventilation is inherently variable and consequently has numerous limitations. Possibly due to the nature of the climate, Western Canadian farmers tend to employ mechanical ventilation systems. These systems can provide a warmer environment with more uniform temperatures at all animal locations than can natural ventilation systems.

Mechanical ventilation systems consist of fans, controls and often other equipment, such as heaters and coolers that condition the air. The initial requirement of a ventilation system is that excess building heat and moisture should be dissipated over and above that required to provide an acceptable temperature and humidity in the ventilated space (Smith, 1972). The equipment outlined above is used to generate sufficient internal air mixing and circulation in order to provide the required levels and uniformity of environmental conditions over a wide range of climatic conditions (Hellickson et al., 1984).

Mechanical ventilation systems for livestock buildings can be classified in terms of pressure, exhaust and neutral systems. Exhaust systems are the most prevalent in dairy facilities. Variations in these ventilation systems are related primarily to the design and location of the inlets. However, there are many other important parameters to be considered, some of which will be outlined in the following sections.

2.6.2.1 Fan Specifications and Control

Livestock housing ventilation involves substantial air flow rates with only a small pressure difference between the inlet and outlet sides of the fans. For this reason, propeller fans, with shrouds fitted closely around the blades, usually dominate fan selection in dairy barns. These fans should be placed on the winter leeward side of a building to minimize outside air interference with fan performance (Wilson et al., 1984). If fans are not connected to a duct system, they should be rated to deliver the required capacity against 3.2 mm water static pressure and should be located at least three metres away from openings such as inlets and doors, to minimize short circuiting (Canadian Farm Building Code, 1977). For houses no less than 12 metres wide, fans may be located at intervals of no less than 12 metres in one sidewall (Curtis, 1983).

Ventilation control of dairy structures during both winter and summer is based generally on the premise that the

level of required ventilation is reflected by building temperature. The primary purpose of ventilation in cold weather is to control moisture. Therefore, due to the length and severity of Prairie winters, humidity control may be a more viable alternative. However, if the ventilation system is controlled by a humidistat only, the humidity requirement may be satisfied only after the inside temperature drops so low as to require supplemental heat in the barn. In any event, thermostats and other sensing equipment used to control the ventilation equipment should be located near the centre of the area ventilated by the controlled fan. Ontario Hydro (1981) recommend that when no supplemental heat is present, a separate thermostat set 3°C above the desired building temperature should be provided for each fan.

2.6.2.2 Air Inlet Design and Airflow Patterns

In determining air distribution in an animal house, perhaps the most important features of a mechanical ventilation system are the design, location and size of inlets. While the rate of air exchange is determined by fan delivery, the uniformity of air distribution depends on the location, design, and adjustment of the air inlets. In both design and operation of a mechanical ventilation system, rated fan capacity at the static pressure value chosen must be balanced by the appropriate area of inlet opening. Munroe et al. (1982) recommended a minimum static pressure differential of 1.3 mm of water at the inlet. In winter,

therefore, the inlet opening width in livestock confinement buildings is typically of the order of 2.5 mm (Curtis, 1983).

The most common inlet is the variable width, narrow slot under the eaves or from the attic along one or both sides of the house or from the attic down the centre of the house. Choice of slot location depends primarily on the width of the building. For houses 12 metres in width, slot inlets should be located along the windward wall only (Curtis, 1983). For wider buildings, slot inlets may be provided on both sidewalls.

Adequate air inlet velocity ensures adequate penetration, turbulence and mixing with the inside air so that cold inlet air will not drop directly on the animals. In general, a low air speed is preferable in the occupied zone but not so low that a sensation of stuffiness exists and that convection currents may be strong enough to dominate the ventilation flow (Smith, 1972). A cold air jet projected horizontally into a warm livestock building through a ceiling-level slot will either fall or remain horizontal depending upon the momentum and density of the jet relative to the room air (Barber et al., 1982). In any system that employs air jets, the jet should entrain sufficient surrounding air so that the velocity dissipates and the temperature rises before the fresh air reaches the stock. The problem is exacerbated in cold weather when, with low ventilation rates, the jet must sustain itself,

possibly over long distances, in order to avoid stagnation in those regions furthest from the inlet. The solution is not only to maintain an inlet air speed of 4 to 5 m/s (Munroe et al., 1982) but also to exploit the Coanda effect, by causing the jet to cling to a smooth roof or ceiling surface.

Under cold weather conditions when low ventilation rates are employed, a static pressure of 1.3 mm water gauge may not always be realizable. In such cases, little air movement takes place and temperature stratification results. This causes an increase in the rate of heat loss through the ceiling or roof. This background led Randall and Battams (1979) to investigate the use of an Archimedes Number as the criterion for control of inlet air jets rather than the usual specification of a jet velocity. The Archimedes Number is defined as the ratio of the Grashof Number to the Reynolds Number squared. Therefore, this number gives a measure of the ratio between buoyancy forces and inertial forces acting on an air jet. The most general form of the Archimedes Number is represented as follows (Randall and Battams, 1979):

$$Ar = g\, d\, (T_2 - T_1)/(V^2\, T) \qquad \text{Eqn. 2.5}$$

where Ar = Archmides Number for a room

g = accaleration due to gravity, m/s^2

d = characteristic dimension, m

T_1 = air temperature of fluid element one, °C

T_2 = air temperature of fluid element two, °C

V = characteristic air speed, m/s, and

T = absolute temperature, °K

Randall and Battams (1979) concluded that the initial path of a ventilating air jet and the stability of the resulting airflow pattern may be determined by calculating a corrected Archimedes Number. According to the stability criterion established by these authors, an inlet jet velocity of 5 m/s will allow the jet to remain horizontal and attached to the ceiling only for outside temperatures greater than 0°C. At temperatures lower than -10°C, the jet will fall immediately upon entering the airspace. A jet velocity of 3 m/s yielded stable horizontal jet flows at temperatures down to approximately 5°C.

Barber et al. (1982) noted the need to improve the existing air inlet systems in cold climate barns. These authors proposed that as an alternative to increasing the jet velocity, the buoyancy forces on the inlet jet can be decreased by preheating the incoming air. This would result in a decreased Archimedes Number and hence improved air circulation patterns.

Unless there are partitions, the resistance to air movement within a building is negligible. The actual environment close to the stock will depend on the degree of mixing between the fresh air and the barn air. At one extreme, unidirectional, short-circuiting of air and other

non-ideal regimes can occur. At the other extreme is highly turbulent flow with no identifiable air paths. Real situations in livestock buildings lie between the two extremes, and flow consists of one or more rotary movements (Randall, 1975). Circulation fans, suspended from the ceiling in strategic locations, may alleviate some mixing problems.

2.6.2.3 Ventilation Rate Design

In order to satisfy the heat balance equation, a particular ventilation rate is required that serves to maintain a comfortable interior temperature and relative humidity. Additionally, minimum ventilation rates may be provided for control of harmful gases and undesirable odours that arise from animal manure. However, these minimum rates could be provided only if the rate of production of contaminants were known and if acceptable concentrations of contaminants were established (McQuitty, 1984). If more air is required for moisture control than for temperature balance, the increased air flow results in increased sensible heat losses, and consequently, supplemental heat may be required to prevent the inside temperature from dropping below the desired level.

Design analysis is based generally on steady-state calculations of animal heat and moisture production, at the assumed indoor temperature. However, as Bates (1976) noted, accurate data from which to make calculations may be difficult to find. In addition, Barber and Ogilvie (1982)

observed that the design of livestock ventilation systems is based on the premise of complete mixing. This assumption involves equating the thermodynamic properties of the exhaust air to the average thermodynamic properties of the bulk airspace. These authors then went on to demonstrate with models the departure from complete mixing in slot-ventilated livestock buildings. Consequently, the authors called for research into the establishment of mixing coefficients to replace the complete mixing assumption in ventilation design calculations.

Winter barn ventilation usually requires low ventilation rates as opposed to high rates during summer. A minimum ventilation rate should be supplied with a continuously-operating, single-speed fan or a variable-speed fan to maintain moisture control in cold weather. Under milder conditions, a range of ventilation rates can be supplied in several ways. A number of constant-speed fans, thermostatically controlled in increments, may be employed. Also, a variable-speed fan or fans are often employed to provide a continuous range of ventilation rates.

2.6.2.4 Insulation and Vapour Barriers

The avoidance of free surface moisture due to condensation is essential to avoid rapid deterioration of most building materials. Thus, ventilation and insulation must be considered together. Where ventilation air exits without thorough mixing, the dewpoint temperature of the inside air will be higher than it would otherwise have been.

Most building materials are porous. In order to retain their thermal insulation properties, interstitial condensation must be avoided. Thus, vapour seals are placed on the internal surfaces (the warm side) of livestock houses, where otherwise temperature and vapour pressure gradients from the inside to the outside of a building would combine to effect penetration of structures by water vapour. Regardless of the type of ventilation system, a vapour barrier is absolutely essential under Prairie conditions.

3. Objectives

Recent trends in dairy livestock confinement housing have resulted in the widespread emergence of large free-stall dairy barns. These housing systems utilize either solid or slatted passageways. The influence of these two manure handling systems on barn heat and moisture production rates is unknown. Accordingly, the data acquisition system at the Department of Agricultural Engineering, University of Alberta, was utilized in the monitoring of six free-stall dairy barns, three with solid passageways and three with slatted passageways. The primary objectives were:

1. To establish the influence of manure handling systems on heat and moisture production in commercial free-stall dairy barns.
2. To determine the total, sensible and latent heat production of confined dairy cows.
3. To provide design data for cattle ventilation and heat balance equations that are appropriate to today's dairy barn facilities.

Additional objectives included:

1. A comparision of the measured data with existing design data to evaluae the validity of the existing data under commercial conditions.
2. An evaluation of ventilation systems in today's free-stall dairy barns.

4. Experimental Procedures and Facilities

4.1 Introduction

In response to the previously described need for animal heat production data reflective of actual commercial production conditions, Feddes and McQuitty (1977,1981) assembled a data acquisition system at the University of Alberta's Department of Agricultural Engineering around a mobile laboratory. In this way, different types of livestock facilities could be monitored over any desired length of time. Provision also was made for a fast turn-around time of raw to processed data via a telephone link to the University's Computing Services Centre.

4.2 Experimental Facilities

Six free-stall barns, three with solid and three with slatted passageways, were chosen from among 25 commercial, free-stall operations examined in the Edmonton area of Alberta. These barns were selected for monitoring on the basis of farmer cooperation, accessibility, feasibility of instrumenting the structure and, last but not least, the manure handling system. The selection of three barns of either floor type was thought to be the minimum number necessary to provide a useful comparision between the two manure handling systems. In addition, the need for design heat production data would be satisfied. A continuous monitoring period of at least 48 hours was chosen. This

length of time, which includes two diurnal cycles, would compensate in part for the dynamic nature of the animal thermal environment under investigation, thermal storage in the barn and the prevailing weather conditions. Each unit monitored was representative of the majority of free-stall dairy barns in Alberta. The study commenced in mid-November, 1983 and was completed by April, 1984. There was no disruption to the normal operation of any of the barns during the monitoring period.

The barns had a number of structural and management features in common. Four barns were of insulated wood-frame construction, one of wood-frame and cinder block, while the sixth was constructed from concrete block. This latter barn was also the only barn without 40-cm wide translucent plastic sections running along the sidewalls. The six barns had insulated false ceilings, and negative pressure, mechanical ventilation systems.

Typically, each barn had a row of stalls along the outer walls and a central feed alley. The larger barns had extra stalls located at one end of the feedbunk. Twice-daily milking at approximately 12-hour intervals was practised in all six operations. The cows in the six units were all Holsteins and were estimated by their respective owners to average 550 kg liveweight. In the three barns with solid passageways, the manure was scraped mechanically to a cross-conveyor or sump and removed from the building on a daily basis. During this operation, the cows were

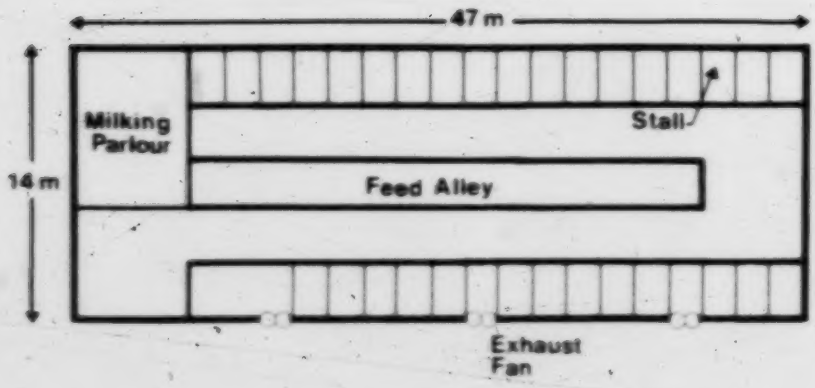
confined to one passageway while the other was being scraped. Table 4.1 summarizes the operational characteristics of the six barns. The building exposure factor (Table 4.1) is the conductive heat loss from the building per animal per degree of temperature difference. A description of the building materials and insulation type in the walls, ceiling and floor was provided by each farmer. The thermal resistances of the building components were then computed using values supplied by the Canadian Farm Building Code (1977) and ASHRAE (1981). The calculated supplemental heat values of Table 4.1 represent the number of light bulbs operating and the fraction of time that these lights were lighting in all barns, except Barn SL-3. This barn was the only barn monitored that had additional supplemental heating in the form of air-to-air heat exchangers and hot-water pipes. Some of the pertinent management and design features of the six barns are described briefly in the following sections.

4.2.1 Barn SO-1 - Solid Passageways

This conventionally-designed structure, shown in Figure 4.1, measured 14 by 47 m and had stalls with straw-covered, earthen floors. The ceiling and walls were insulated with glass fibre having RSI values of 2.1 and 3.5 ($m^2.°C)/W$, respectively. The central feedbunk was filled by a conveyor, the cows being fed alfalfa haylage and a grain ration in the parlour. Ventilation was provided by three evenly spaced, thermostaticaly-controlled, 61-cm diameter

TABLE 4.1 SUMMARY OF OPERATIONAL CHARACTERISTICS, (MEAN VALUES).

Passageways	Barn		
SOLID:	SO-1	SO-2	SO-3
Number of 550 kg Cow Equivalents	60	37	42
% Cows Milking	97	85	86
Milk Production, kg/(cow.day)	24.5	20.0	18.9
Water Consumption, kg/(cow.day)	80.0	87.2	71.1
Stocking Density, m^2/cow	10.5	12.7	9.6
Stocking Rate, % of Barn Capacity	86	76	81
Exposure Factor, kJ/(h.°C.cow)	32.0	25.0	29.7
Supplemental Heat, kJ/(h.cow)	35.0	34.1	34.3
SLATTED:	SL-1	SL-2	SL-3
Number of 550 kg Cow Equivalents	154	61	150
% Cows Milking	96	95	100
Milk Production, kg/(cow.day)	24.9	16.0	22.3
Water Consumption, kg/(cow.day)	69.6	50.2	74.2
Stocking Density, m^2/cow	4.8	9.1	5.6
Stocking Rate, % of Barn Capacity	100	81	100
Exposure Factor, kJ/(h.°C.cow)	13.4	33.3	9.6
Supplemental Heat, kJ/(h.cow)	6.9	83.6	39.2



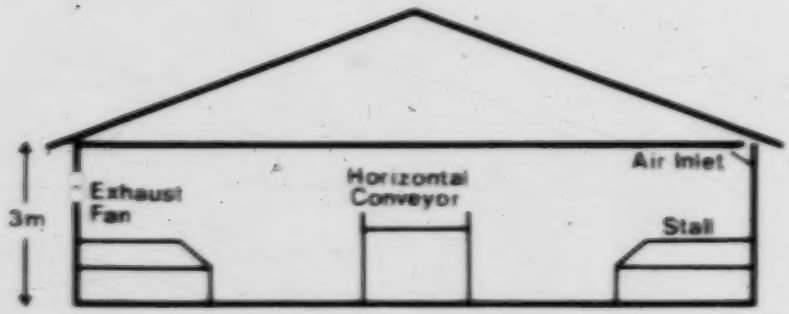


Figure 4.1 Barn SO 1 - floor plan and cross section

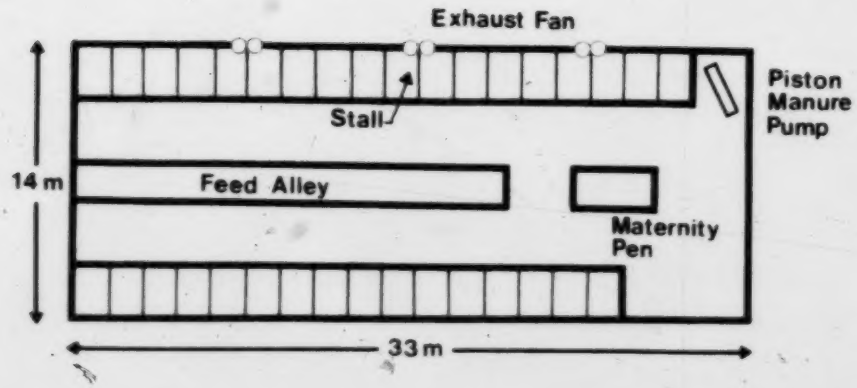
fans, located 1.17 m down the 2.9-m high, leeward wall. One fan was two-speed, the others being constant-speed units. Fresh air entered through a discontinuous, adjustable, slot inlet along the opposite, or windward, wall. Manure was scraped daily into a sump located at one end of the barn.

4.2.2 Barn SO-2 - Solid Passageways

This barn also had straw-covered, earthen-floored stalls and measured 13 by 36 m (Figure 4.2). The barn was insulated with glass fibre, RSI value of 3.5 ($m^2.°C)/W$, in the walls and ceiling. The cows were fed in a central feedbunk, the baled hay being brought into the barn twice daily by tractor. A protein supplement was provided daily in the milking parlour. Three evenly spaced, thermostatically-controlled, constant speed, 40-cm diameter fans were located 0.35 m down the 2.6-m high, leeward wall. Fresh air was provided by an adjustable inlet in the centre of the ceiling. A tractor-scraper cleaned the passageways daily, delivering the manure into a piston, manure-transfer pump.

4.2.3 Barn SO-3 - Solid Passageways

As in Barn SO-2, the cows in this unit were fed baled hay from the drive-through central feedbunk (Figure 4.3) that was used both for storage and feeding. The animals also received a grain ration in the parlour. The barn area was 14 by 33 m. Straw was used liberally for bedding on the earthen-floored stalls. The walls were insulated with glass fibre batts, RSI value of 2.1 ($m^2.°C)/W$, while the ceiling



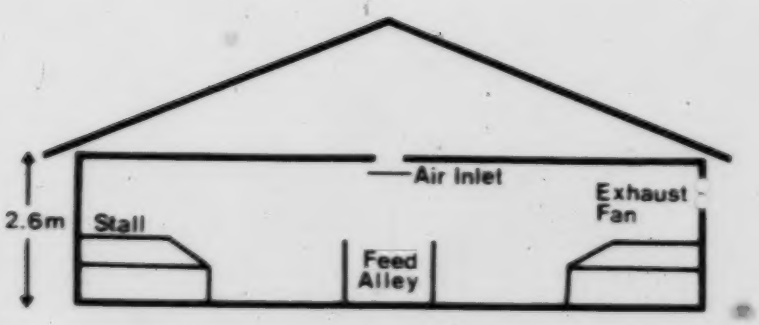
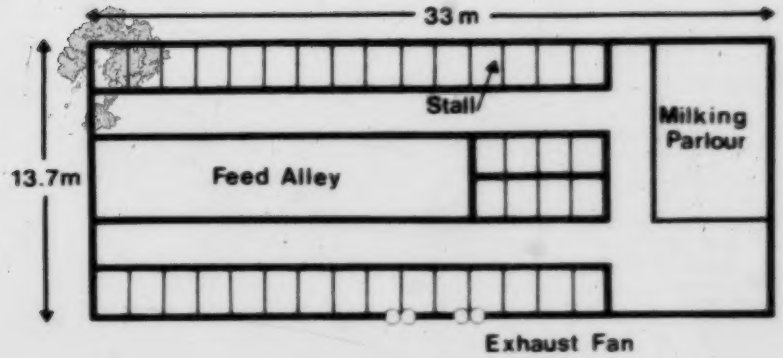


Figure 4.2 Barn SO 2 - floor plan and cross section.



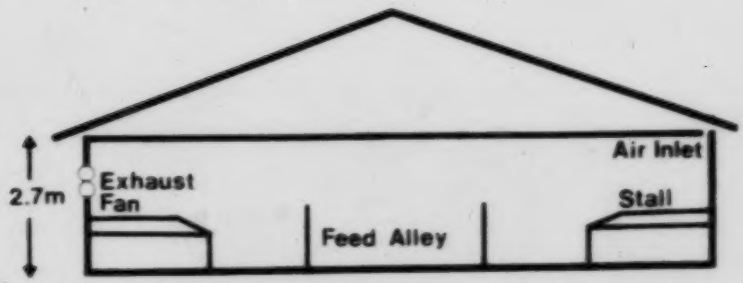


Figure 4.3 Barn SO-3 - floor plan and cross-section.

contained glass fibre having an RSI value of 3.5 ($m^2.°C$)/W. Two 61-cm diameter fans, one two-speed, the other single-speed, provided ventilation, with fresh air entering through discontinuous non-adjustable, slot inlets on the opposite wall. The fans were mounted side by side 1.1 m down the 2.9-m high, leeward wall. A tractor-scraper cleaned the alleyways daily and removed the manure from the barn by utilizing a cross-conveyor.

4.2.4 Barn SL-1 - Slatted Passageways

This large building, which had been constructed in two stages, measured 12 by 56 m (Figure 4.4). The ceiling was insulated with wood shavings to a depth of 15 cm with an estimated RSI value of 3.5 ($m^2.°C$)/W (Canadian Farm Building Code, 1977). The walls contained glass fibre having an RSI value of 2.1 ($m^2.°C$)/W. A belt conveyor transported an alfalfa-high moisture barley feed along the central feedbunk. Sawdust was spread weekly on the concrete-floored free-stalls. Ventilation was provided by four continuously-running, 40-cm diameter, constant-speed fans on the leeward wall, with discontinuous, non-adjustable, slot openings on the opposite wall providing the fresh air. In the older part of the barn, two fans were located 0.61 m down a 2.34-m high, cinder block wall. The other two fans were located 0.61 m down a 2.74-m high, wood-frame wall. The nearly-full, manure pit was about to be cleaned out approximately two weeks after monitoring. Wash water was added intermittently to the pit.

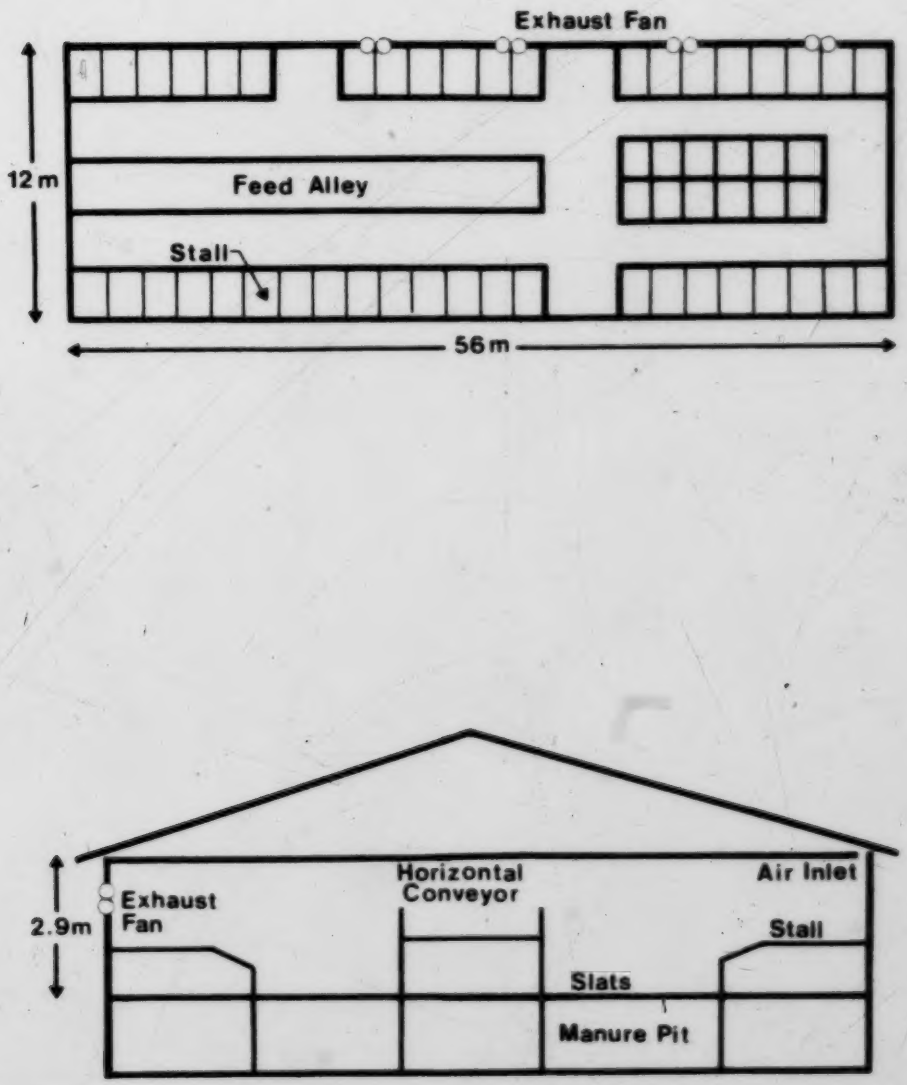


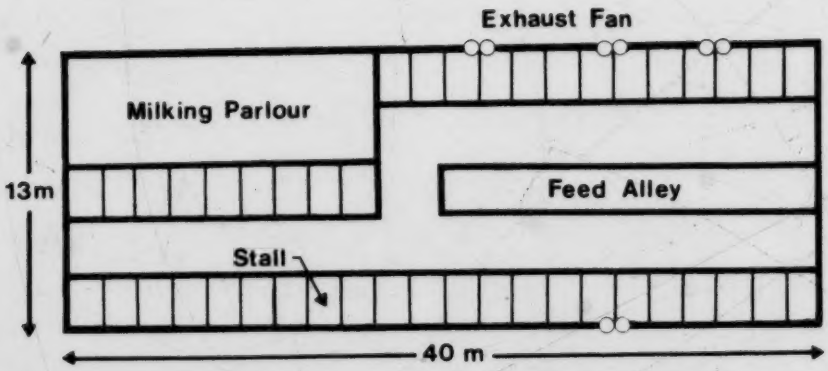
Figure 4.4 Barn SL-1 - floor plan and cross-section.

4.2.5 Barn SL-2 - Slatted Passageways

This barn was the only completely concrete block structure monitored and measured 13 by 50 m (Figure 4.5). The only insulation was provided by 5 cm of vermiculite in the ceiling. This had an estimated RSI value of 1.5 (m^2.°C)/W (Canadian Farm Building Code, 1977). Barley/oat haylage was brought to a centre feedbunk by conveyor. Ventilation was provided by two 30-cm and one 50-cm diameter, manually controlled, constant-speed fans, located 0.6 m down the 2.5-m high, leeward wall. A fourth fan on the windward wall was not turned on during the monitoring period, the farmer having decided that the barn was very cool. Fresh air entered through fixed openings in windows in the sidewalls. The manure pit was almost empty during the monitoring period, the cows having been outside prior to that.

4.2.6 Barn SL-3 - Slatted Passageways

This large unit, having an area of 13 m by 70 m., is shown in Figure 4.6. Insulation was provided by two blankets of fibre, RSI value 2.1 (m^2.°C)/W, in the walls and glass fibre, RSI value 3.5 (m^2.°C)/W, in the ceiling. A conveyor belt along the central feedbunk carried the alfalfa haylage and rolled oats to the animals. Ventilation was provided by two thermostatically-controlled, constant speed, 70-cm diameter fans located directly opposite each other about one-third the way along the length of the barn. They were mounted 1.0 m down the 2.7-m walls. Two heat



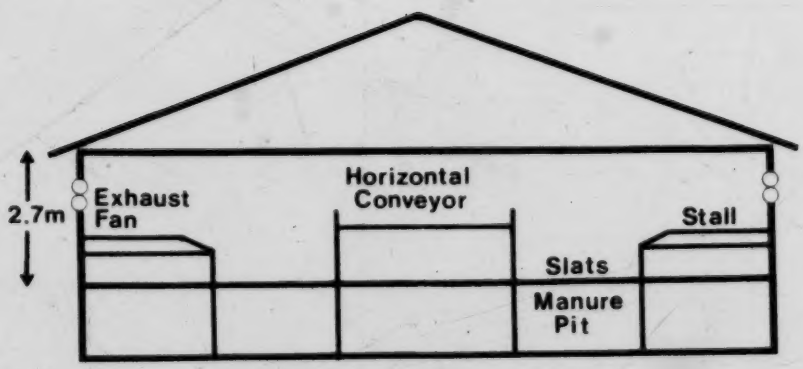
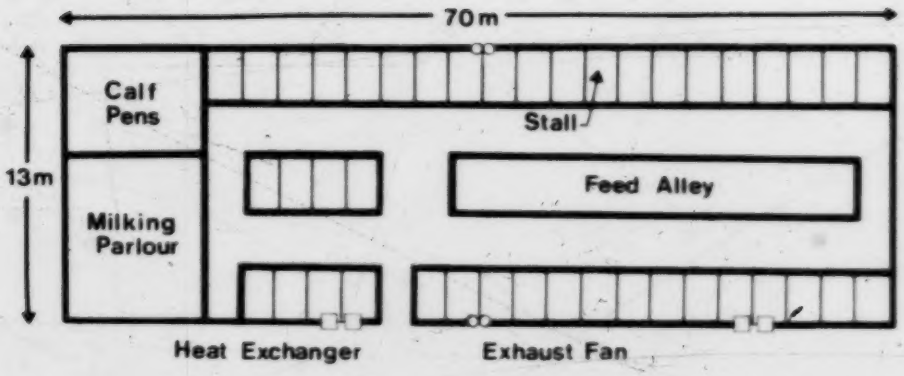


Figure 4.5 Barn SL-2 - floor plan and cross-section.



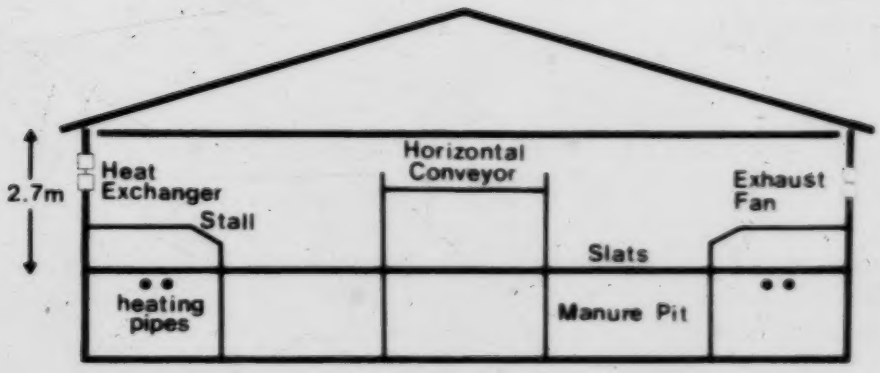


Figure 4.6 Barn SL-3 - floor plan and cross section

exchangers (Del Air, Model A-800) were located in the leeward wall, 1.9 m from the ground, at both ends of the barn. In addition to recovering heat, these assisted in barn ventilation. Fresh air entered through discontinuous slot inlets on both sidewalls. Two 3.8-cm inside diameter, hot-water pipes ran underneath the earthen-floored stalls, for approximately three-quarters of the way around the barn. As the primary purpose of the pipes was to maintain dry and comfortable conditions, there was no need for any heating/ventilating interlock. Five 90-cm diameter, ceiling fans were spaced evenly and longitudinally along the centre of the barn to assist in air circulation. This was also the only barn to contain animals other than lactating cows. Six calves and two bulls also occupied the building. The conversion of calf to cow-equivalent units was based on data from Yeck and Stewart (1959). The corresponding conversion for the bulls was based on metabolic weight (liveweight raised to the power of 0.75). Finally, the manure pit was about to be emptied at the time of monitoring.

4.3 Experimental Procedures and Instrumentation

To perform a simultaneous heat and moisture balance on the barns describd above, the mobile data acquisition system, developed by Feddes and McQuitty (1977,1981), was employed to continuously monitor the thermal environment over a continuous 48-hour period. This involved measuring air temperatures within the barns and withdrawing samples of

air from the barn for relative humidity determination. During the monitoring of a particular barn, the 3.5 by 8.0 m, air-conditioned laboratory was located as close as possible to the livestock facility so as to minimize the exposure of the air sampling lines to the outside winter environment. All the sampling lines and extension cables lead from the livestock facility to the microprocessor-controlled data logger or other equipment housed in the laboratory via a 10-cm diameter, electrically-heated conduit. This conduit prevented condensation of moisture in the air sampling lines. Within a typical barn, the various sensors were connected to two multi-conductor extension cables. In this way, monitoring could be suspended temporarily by disconnecting the two cables and pulling the laboratory away to another location. Figure 4.7 is a schematic of the instrumentation arrangement for a typical barn monitored.

As ventilation heat loss is the major component of the barn energy balance, the accurate measurement of ventilation rates was of utmost importance. Insulated discharge ducts, incorporating air straighteners to help in stabilizing the velocity pattern, were constructed downstream of each exhaust fan. The monitoring locations of the air flows in each duct were as prescribed by Jorgenson (1983). According to a particular fan size, three duct sizes were fabricated, .31 m^2, .40 m^2 and .62 m^2. All ducts measured 3.66 m long. A specially-fabricated transition piece was required when

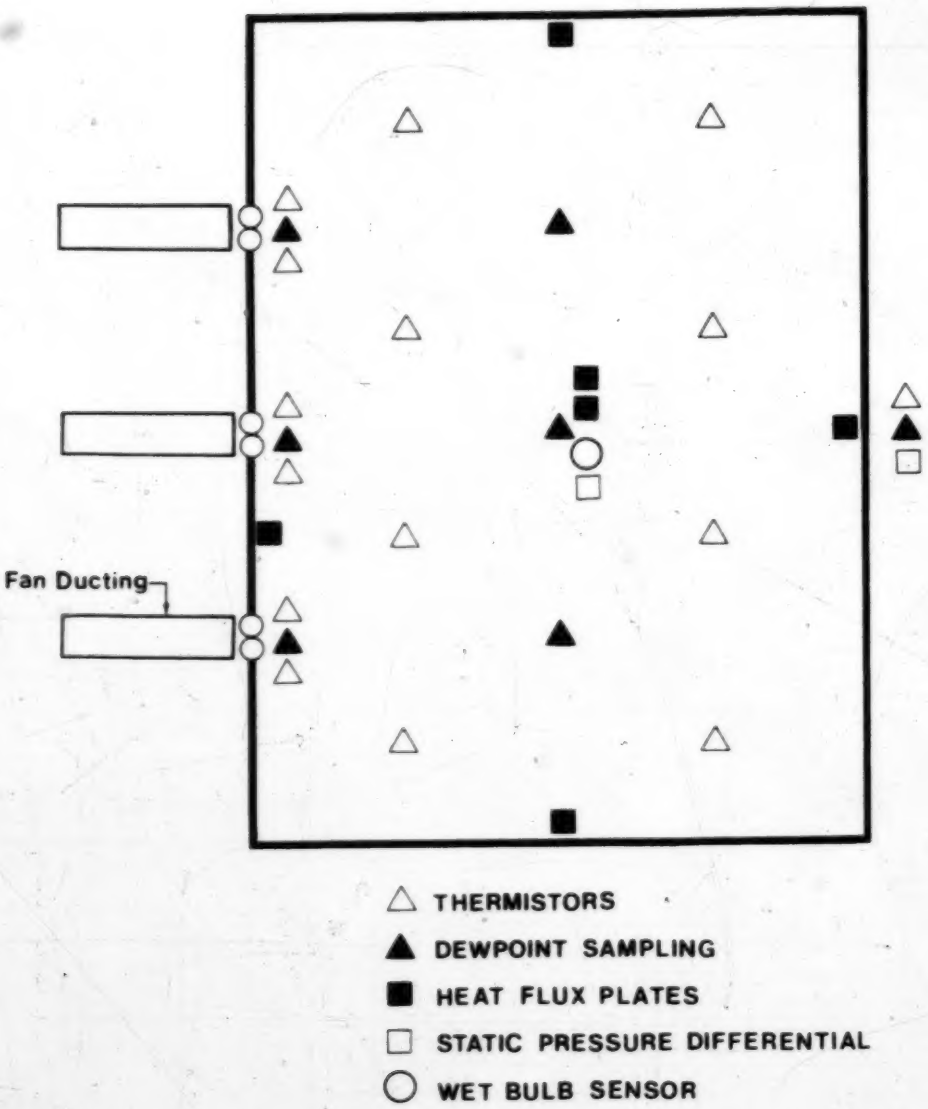


Figure 4.7 Instrumentation arrangement for a typical barn monitored.

fitting a duct to a heat exchanger.

A thermistor anemometer (Model TA3000, Airflow Developments, Buckinghamshire, England) was used to measure the air-flow rates over a 25-point duct profile, 3 to 4 times daily during the monitoring period. A hot-wire anemometer (Sierra Instruments, Redlands, Cal.) was used to check these readings. Both instruments were calibrated regularly in an air-velocity calibrator designed and constructed for the purpose by the Department of Mechanical Engineering, University of Alberta. Air flow in the calibrator was varied by regulating pressure drop across a standard orifice using a Validyne pressure transducer (Sierra Instruments, California). If climatic conditions were windy and thought to influence fan speeds, supplemental air-flow measurements were taken.

Magnetically-activated electronic switches, utilizing the Hall Effect for sensing a magnetic field, were mounted on those fans that were either variable or two-speed in operation. These sensors monitored the speed of the fans at four-minute intervals. The sensor itself was placed on the fan housing and was activated by a magnet secured to the rotating fan shaft. The pulses were integrated and the output voltage was associated with a fan speed. By calibrating air-flow against fan speed over the entire range of a fan, a functional relationship was developed between the two parameters.

The static pressure differential between the inside and outside of a barn, which was measured using a low-range differential pressure transducer (Validyne, Model DP45, Sierra Instruments, California), was assumed to have a negligible effect on fan performance due to the low pressure differentials found. In the case of constant-speed fans, a thermistor (Model UUB 31J1, Fenwal Electronics, Framingham, Mass.) was placed in the fan ducting to determine the fan on/off state at 4-minute intervals. In circumstances where a particular fan was not operating during the course of an experimental run, and that fan window was not fitted with an anti-backdraught louvre, the window was boarded up so as to prevent interference with the existing barn inlets.

In order to determine the enthalpy of the inlet and exhaust air, the respective dry-bulb temperatures and dewpoints had to be measured. Thermistors were placed at the top and bottom of each fan and outside of each barn. A thermistor was placed in the attic of each barn to assist in determining the heat lost through the ceiling. In addition, each barn was divided into eight sections, quarters by length and halves by width, and a thermistor located, either 40 cm below the ceiling or at animal level, at the centre of each section, to measure the actual ambient temperature throughout the barn as opposed to exhaust conditions. The thermistors were placed in a constant-current circuit which gave voltage outputs in the range 0.298 to 9.310 volts, corresponding to -40 to +40°C, respectively. Calibration of

the thermistors and subsequent development of equations relating temperature to the electrical resistance of the sensor had been performed by the manufacturer. Appendix A lists the the equations used to derive resistances and temperatures, while an error analysis of the data measurement system is provided in Appendix B.

Dewpoints of outside, inside and exhaust air were recorded by drawing samples via plastic tubing, through a dewpoint hygrometer (Model 880, Cambridge Systems, Mass.) housed in the mobile laboratory. This instrument utilizes the dewpoint condensation principle in determining the concentration of water vapour in an air sample. However, whenever in the course of the experiment the outside air temperature dropped below approximately -8°C, the instrument was unable to accurately record its dewpoint. In such instances, dewpoint data from a nearby meteorological station (Edmonton International Airport) were substituted. In any event, due to the dryness of such cold air, any errors involved in this procedure were considered to influence the psychrometric calculations only very marginally. Care was taken not to allow the sample air temperature to fall below its dewpoint en route to the hygrometer via the previously-mentioned heated conduit. A check on the measured ambient dewpoints was provided by recording wet-bulb temperatures in the centre of each barn using an aspirated, thermistor-based wet-bulb sensor. Hand-held psychrometers also were used regularly to measure

the instantaneous dry-bulb, and wet-bulb temperatures, thus checking the sensor outputs.

Conductive heat losses were measured using heat-flux plates described by DeShazer et al. (1982). These were attached to the inside surface of a building, thereby excluding the solar radiation component on the plate. An infrared pyrometer (Omega Engineering, Stamford, Conn.) was used to determine the positioning of a heat-flux plate. This was accomplished by scanning the surface temperatures of each structural component of a barn, that is, walls, floor, and ceiling. A location then was chosen such that its surface temperature was representative of that surface.

The measured heat transmission through the structural components was checked against those calculated, from the known thermal resistances of the building components and the temperature difference across the components. In addition, a heat-flow plate (Concept Engineering, Old Saybrook, Conn.) placed on the inside surfaces served as a check to the heat-flux plate heat-flow rates. It also was used as the standard in the calibration of the individual heat-flux plates. This necessitated the simultaneous placement of the heat-flow plate and the heat-flux plates on a heated copper plate. Linear regression equations, relating the temperature differential across each heat-flux plate to heat flux, were developed subsequently.

In Barn SL-3, supplemental heat output from the imbedded water pipes was determined by placing

thermally-wrapped thermistors on the inlet and outlet pipes at the barn entry and exit points, and by measuring the water-flow rate with an ultrasonic Doppler flow-meter (Polysonics Flowmeter, Houston, Tx.). This instrument, which utilizes the Doppler principle as its basis for operation, was calibrated against a magnetohydrodynamic flow-meter (Type 1803 Sans-CA, Foxborough CO. Ltd., Le Salle, Que.) in the Civil Engineering Hydraulics Laboratory, University of Alberta. The flow-meter transducer was placed in excess of 20 diameters downstream from any constriction, elbow or junction in the pipe. Measurements of hot-water flow rates were taken only daily as the flow rates due to the continuously-running, circulation pump were constant. The proportion of heat flowing upwards through the earthen-floor was measured using the aforementioned heat-flow plate and was found to be 0.7 times the total heat output from the pipes.

In the same barn, sensible heat exchange in the heat exchangers was determined from the supply outlet and outside temperatures, the measured fraction of time that heat was recovered in each exchanger, and the exhaust air-flow rates. A possible source of sensible heat, running motors as found on augers, belt conveyors and fans, was considered to be negligible and, consequently, was not measured. In any case, such heat sources are typical of practically all free-stall dairy facilities and, therefore, any minor errors stemming from their omission in the calculations are spread

across all the barn data.

Several other parameters that related indirectly to barn heat and moisture loads and helped explain or verify trends and variations in the data were measured. Water consumption by the animals also was measured, using a water meter (Neptune Meters, Toronto, Ont.) placed in the water-trough feed line. Many of the more specific management features associated with each barn were of interest. Animal feed type, in addition to total milk production, were recorded. The type and amount of bedding were considered. Actual cleaning, milking and feeding times were recorded as these too would help explain trends and variations in the heat production data. Table 4.2 summarizes the primary sensors, their location and scanning rate.

4.4 Data Processing and Analysis

The output signals from each sensor were received and processed by the data logger. This usually necessitated signal conditioning to a 1-10 volt range to effect analogue-digital-converter compatability. In order to sample air from more than one location within a barn, an automatic sampler permitted sequential sampling from a total of 15 locations. Solenoid-activated valves were placed on each sampling line and a time-clock allowed hourly sequencing of the 15 locations. The data logger had the capacity to handle input from 144 channels, 32 analog and

TABLE 4.2 SUMMARY OF THE PRIMARY SENSORS, THEIR LOCATIONS AND SCANNING RATE, FOR A TYPICAL BARN MONITORED.

Sensor Type and Sampling Rate	Location	Number of Sensors
Thermistors: (20-minute)	attic	1
	outside	1
	40 cm below ceiling level	5
	cow level	3
	wet-bulb	1
Thermistors: (4-minute)	at each fan (high and low)	2 per fan
	downstream from fan	1 per duct
Heat-flux plates: (20-minute)	ceiling	1
	walls	4
	floor	1
Sequential dewpoint sampling: (30-minute)	exhaust	1 per fan
	ambient	3
	outside	1
Static Pressure differential: (4-minute)	centre of barn	1
RPM sensor: (4-minute)	variable or 2 speed fans	1 per fan
Water consumption: (daily)	trough water line	1
Wet bulb meter: (4-minute)	centre of barn	1

112 thermistor only. The former were scanned every 4 minutes while the latter are scanned in 4-minute multiples as specified by the manually-adjusted time clock. Such frequent scanning rates compensated to some extent for the dynamic nature of the environment under investigation. In the course of a typical monitoring period, 12 analog inputs and 28 thermistor inputs were used. The data logger recorded the environmental information on paper tape throughout an entire sampling period or, if necessary, a portable terminal and three-pen chart recorder. The latter was useful in instances such as in determining heat-exchanger defrost cycles. The digital paper-tape data then were transformed into raw voltage data by tape-reading facilities at the Computing Services Centre, University of Alberta, for further processing on a mainframe computer. Utilizing a FORTRAN IV computer program available within the Department of Agricultural Engineering, the disc-stored data then were processed into their real units and averaged over each hour. To assist in data analysis, some data were plotted on a Tektronix 4054A graphics terminal via the Michigan Terminal (operating) System that is supported by the Computing Services Centre.

4.5 Heat and Moisture Balance

Using standard psychrometric equations (ASHRAE, 1981), the specific humidities, enthalpies and specific volumes of the incoming and exhaust air were calculated utilizing the

same FORTRAN program as above. The unique wiring configuration of each barn necessitated that the program be altered each time a particular barn heat balance was performed. The product of the measured duct air speeds and the duct areas yielded the ventilation rate for that barn. The gains in total heat and moisture contents of the air as it passed through the barn then were determined. Adding the conductive heat losses and ventilation heat losses and subtracting the supplemental heat gains yielded the animal total heat output together with the latent heat arising from the animals and by evaporation of moisture from wet surfaces within the building. Animal sensible heat output was represented by the difference between these total and latent heat data. Appendix C contains barn heat and moisture balance equations.

Animal heat and moisture production data may be expressed in a number of ways, for example on a metabolic weight basis, or on a liveweight basis. Dairy cattle design heat production values have been expressed traditionally on a 1000-lb liveweight basis. The SI unit of comparable size was determined to be a 500 kg liveweight unit. Therefore, the production values obtained were converted from a 550 kg basis to 500 kg basis for analysis purposes.

5. Results and Discussion

5.1 Environmental Control

Tables 5.1A and 5.1B lists some of the pertinent environmental parameters for the six barns monitored. The variation in outside temperature, from an average temperature of -10.0°C for the first barn monitored, SO-1, to an average of 5.8°C for the last barn monitored, SO-3, influenced the ventilation rates required for temperature and moisture control in all the barns and, consequently, the heat and moisture production in the barns. In addition, the range of this outside temperature also exerted an influence on barn ventilation rates. This range, during monitoring of Barn SO-2, for example, was 25°C. However, the ventilation system response in each barn can be gauged by the range of inside temperature compared to the outside temperature. For example, from Table 5.1A, the outside temperature for Barn SO-1 varied from -5 to -18°C while the inside temperature remained relatively constant, ranging from 3 to 6°C at the fan outlets. The average inside temperature range for all six barns was only 5.8°C, which shows the relatively steady-state environment that may prevail in dairy barns, even with quite substantial variations in outside temperature.

Environmental conditions within a barn, as determined by the recommended environmental parameter limits, were by and large, quite satisfactory. The observed temperatures

TABLE 5.1A SUMMARY OF ENVIRONMENTAL PARAMETERS FOR THREE SOLID PASSAGEWAY BARNS, (MEAN VALUES).

Parameter	Barn		
	SO-1	SO-2	SO-3
Ventilation Rate, L/(s.cow)	41.7	48.5	75.9
Range	(23/64)	(22/73)	(58/76)
Outside Temperature, °C	-10.0	-8.7	5.8
Range	(-5/-18)	(6/-19)	(16/-1)
Exhaust Temperature, °C	4.3	7.4	13.6
Range	(3/6)	(5/14)	(10/19)
Animal Level Temperature, °C	4.0	8.2	13.6
Range	(2/6)	(7/13)	(10/19)
Ceiling Temperature, °C	5.5	8.9	14.0
Range	(5/7)	(8/14)	(10/19)
Inside Relative Humidity, %	88	84	71
Range	(82/100)	(64/95)	(44/84)
Static Pressure Differential, mm W.G.	4.20	0.64	0.77
Range	(2.0/5.0)	(0.5/0.8)	(0.6/0.8)

TABLE 5.1B SUMMARY OF ENVIRONMENTAL PARAMETERS FOR THREE SLATTED PASSAGEWAY BARNS, (MEAN VALUES).

Parameter	Barn		
	SL-1	SL-2	SL-3
Ventilation Rate, L/(s.cow)	40.6	49.1	28.5
Range	(38/44)	(46/69)	(28/29)
Outside Temperature, °C	-1.7	-5.1	-4.2
Range	(3/-7)	(1/-10)	(4/-12)
Exhaust Temperature, °C	12.9	7.2	15.5
Range	(11/15)	(5/9)	(12/18)
Animal Level Temperature, °C	11.9	7.2	13.0
Range	(10/13)	(5/10)	(9/17)
Ceiling Temperature, °C	13.5	7.4	13.8
Range	(12/16)	(6/9)	(9/18)
Inside Relative Humidity, %	73	82	70
Range	(65/83)	(79/90)	(64/80)
Static Pressure Differential, mm W.G.	0.51	0.40	1.02
Range	(0.3/1.0)	(0.3/0.8)	(0.8/1.3)

varied from as low as 3°C in Barn SO-1 to 19°C in Barn SO-3. These temperatures are well within the range prescribed by The Canadian Farm Building Code (1977) of -6°C to 24°C for dairy cattle.

Vertical temperature gradients were estimated by comparing the temperatures measured at approximately 40 cm below ceiling level and those at animal level, in each barn. Somewhat surprisingly, and with the exception of Barn SO-1, these gradients were only 1.6°C or less despite static pressure differentials being maintained at very low levels (Tables 5.1A and 5.1B). The average static pressure measurements for the five barns with low static pressure differentials was 0.67 mm which does not compare favourably to the minimum recommended level of 1.3 mm static pressure prescribed by Munroe et al. (1982). Incidently, four of these five units had discontinuous, non-adjustible slotted or window air inlets. Barn SO-1, which had a static pressure differential of 4.2 mm, was a well-sealed unit with adjustable slotted-air inlets. In any event, the poor inlet design in some barns would undoubtedly result in poor air mixing and stagnant zones. The extent of such departures from complete mixing of the occupied air, however, could not be directly assessed.

Barn relative humidities tended to be higher than normally considered desirable, particularly in the units with solid passageways. Barns SO-1 and SO-2, for example, had average relative humidities of 88 and 84%, respectively.

Such high figures reflected the tendency of all the operators to ventilate on the basis of temperature control, even in those units where thermostats were not used. Thus, relative humidities tended to reflect outside temperatures in that the values were higher during colder weather. The use of heat exchangers in Barn SL-3 appeared to contribute favourably to the ambient conditions recorded within the barn (Table 5.1B). In addition, within the same barn, the heated earthen floors probably assisted in maintaining an average humidity of 70%, the lowest value recorded.

The Canadian Farm Building Code (1977) provides only general guidelines for ventilation rates in dairy barns. A rate of 26 L/(s.cow (500 kg)) for moisture control alone is recommended while 90 L/(s.cow (500 kg)) is deemed necessary for summer barn conditions. As mentioned already, the adequacy of ventilation may be gauged by examining the inside environment. However, situations may have arisen where the inside environment was determined largely by the operating ventilation rate. This would be particularly true in instances of poor thermostatic control or with no fan control at all. In any event, the low temperature and high relative humidity measured in Barn SO-1 may indicate that the average ventilation rate of 37.9 L/(s.cow (500 kg)) (Table 5.1A) was too high for the prevailing cold outside temperature. Possible short-circuiting of the inlet air substantiate this notion. On the other hand, the high ambient temperatures found in Barn SL-3, in view of the

recorded outside temperatures (Table 5.1B), suggest that the average ventilation rate of 25.9 L/(s.cow (500 kg)) was too low. All other ventilation rates (Table 5.1), particularly those in Barns SO-3 and SL-1, would seem reasonable with respect to the respective inside environments.

5.2 Building Heat Balance Components

In a heat balance for an animal confinement building, the major component of heat losses normally is that due to ventilation. Table 5.2 shows that this varied from 90% of the total heat loss in Barn SO-1 to 96% in Barn SL-1. High ventilation losses and high levels of insulation were recorded in all six barns. Also, cloudy weather persisted throughout most of the monitoring period. For these reasons, heat gains due to solar radiation were not measured directly. However, the structural heat-flow measurements using the heat-flux plates took solar radiation into account. The good agreement between attic temperatures and outside temperatures supported this omission of solar heat gains. The longwave radiation losses at night also were ignored. Figure 5.1 illustrates the conductive heat losses by structural component for a typical barn, Barn SO-1. The greatest source of conductive heat loss in all barns was through the walls.

TABLE 5.2 MEAN BUILDING HEAT BALANCE COMPONENTS BY SOURCE FOR SIX BARNS.

Passageways	Barn			Mean Values
SOLID:	SO-1	SO-2	SO-3	
Total Barn Heat Production, kJ/(h.cow (500 kg))	4122	4489	4561	4391
Conductive Heat Loss, kJ/(h.cow (500 kg))	417	366	209	331
Ventilation Heat Loss, kJ/(h.cow (500 kg))	3705	4123	4352	4060
Conductive/Total	0.10	0.08	0.05	0.08
SLATTED:	SL-1	SL-2	SL-3	
Total Barn Heat Production, kJ/(h.cow (500 kg))	4250	4251	3377	3959
Conductive Heat Loss, kJ/(h.cow (500 kg))	177	371	170	239
Ventilation Heat Loss, kJ/(h.cow (500 kg))	4073	3880	3207	3720
Conductive/Total	0.04	0.09	0.05	0.06

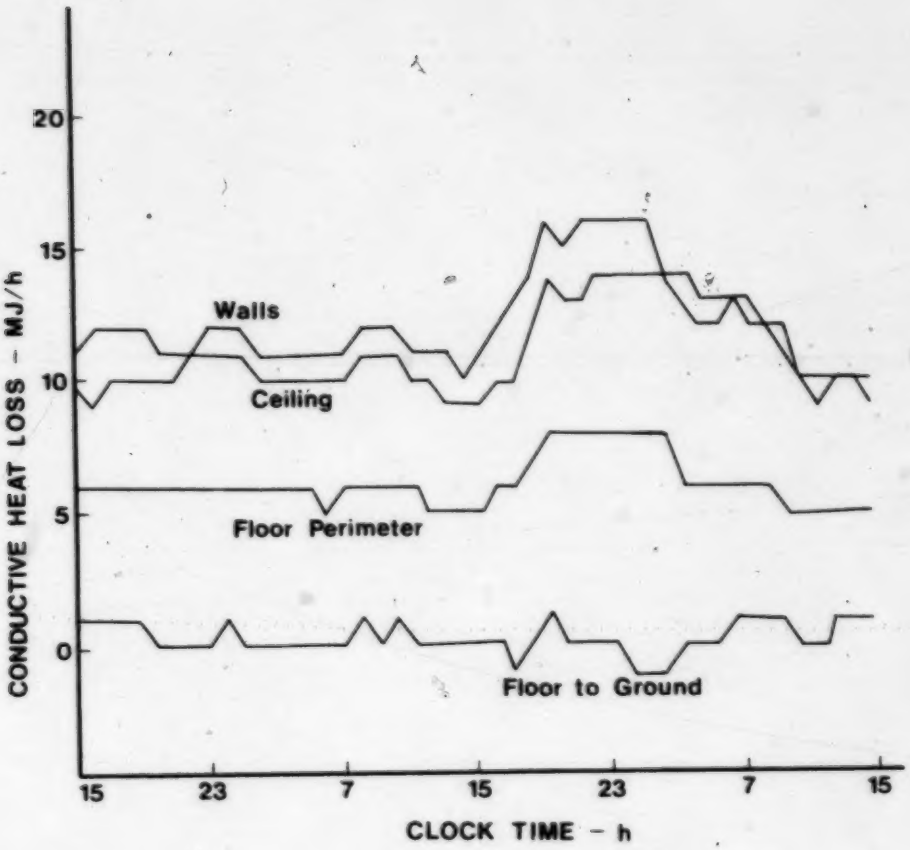


Figure 5.1 Typical conductive heat losses by structural component - Barn SO-1.

5.3 Animal Heat Production

The mean measured animal total, latent and sensible heat production, in kJ per hour per cow of 500 kg, are given in Table 5.3. While all six barns were not maintained at the same temperature (Table 5.1A and 5.1B) during the period in which each was monitored, the results were reasonably consistent, particularly with respect to total heat production.

Temperatures in all the units were considered to be within the zone of thermoneutrality for lactating cows and, consequently, variation in total heat production could not be explained in terms of temperature alone. Other probable contributing factors to this variation included level of milk production and stage of lactation, feed energy intake, stocking density and its influence on animal activity, and management differences between herds. The usual higher stocking densities associated with free-stall units with slatted passageways than in those with solid passageways existed in this study, the average densities varying from 6.5 m^2/cow in the former to 10.9 m^2/cow in the latter (Table 4.1). Milk production ranged from 16.0 kg/(cow.day) to 24.9 kg/(cow.day) (Table 4.1). While the animals in two barns with solid passageways were fed hay, those in the units with slats were fed mainly haylage. Hence, many variables other than temperature may have altered the total heat load in a barn. The previously-discussed, environmental stress factors, as opposed to possible nutritional ones,

TABLE 5.3 MEASURED TOTAL, SENSIBLE AND LATENT HEAT PRODUCTION, kJ/(h.cow (500 kg)).

Passageways	Barn			Mean Values
SOLID:	SO-1	SO-2	SO-3	
Temperature °C	4.3	7.4	13.6	8.4
Total Heat Production	4090	4458	4530	4360
Sensible Heat Production	2709	2686	2409	2602
Latent Heat Production	1381	1772	2121	1758
Latent Heat/Total Heat	0.34	0.40	0.47	0.40
SLATTED:	SL-1	SL-2	SL-3	
Temperature °C	12.9	7.2	15.5	11.8
Total Heat Production	4244	4175	3341	3920
Sensible Heat Production	2444	2574	1943	2320
Latent Heat Production	1800	1601	1398	1600
Latent Heat/Total Heat	0.42	0.38	0.42	0.41

undoubtedly would influence overall animal performance in some cases and possibly heat output as well, but such factors could not be determined within the scope of this study.

The only barn that differed from the other units in terms of total heat production was Barn SL-3. Within this building, the low heat production values could be accounted for by relatively high ambient temperature (Table 5.1B) and the high stocking density (Table 4.1). The latter management feature may have tended to lower total heat production per animal due to reduced heat of activity.

In general, the latent heat removed by ventilation from the barns with solid passageways was higher than that from those with slatted passageways by almost 10%. However, the latent heat loads in the three warmest barns (Table 5.1) were, on average, higher by nearly 12% than those in the three cooler barns. Thus, the temperature at which a free-stall dairy barn is operated in practice would seem to have an influence on moisture loads comparable to the manure handling system. The quantity and quality of bedding used also may have influenced moisture loads. The extent of these influences, however, did not appear to be other than minor and was not quantified in this study.

The measured latent heat to total heat ratios for the three barns with solid passageways averaged 0.40, while the ratios for the slatted units averaged 0.41 (Table 5.3). The similarity of these results would suggest that the ratio of

latent to total heat removed by ventilation is more a characteristic of free-stall housing rather than the manure handling system used within them. The average ratios for the three coolest and three warmest barns were 0.37 and 0.44, respectively. This again emphasizes the significance of barn temperature on moisture loads, the higher the temperature the greater the evaporation taking place from wet surfaces. Increased respiratory evaporation or sweating of the animals in the three warmest barns or increased urination in the colder barns may partially explain this relationship between barn latent heat loads and barn temperature. However, the average temperatures of the three warmest and three coolest barns, 14°C and 6.3°C, respectively, tend to discount this theory. Figure 5.2 is a graph of the calculated heat balance components as a function of time for a typical barn, Barn SL-3. Regression equations relating ambient temperature to free-stall heat production for the two manure handling systems are given in Appendix D.

5.4 Comparision of Results with Design Data

The measured animal heat production rates were compared with those calculated from equations derived by Yeck and Stewart (1959) and Strom and Feenstra (1980). As previously mentioned, the equations of the former authors were based on data more appropriate to a tie-stall dairy facility so that a direct comparision may seem inappropriate. However, as

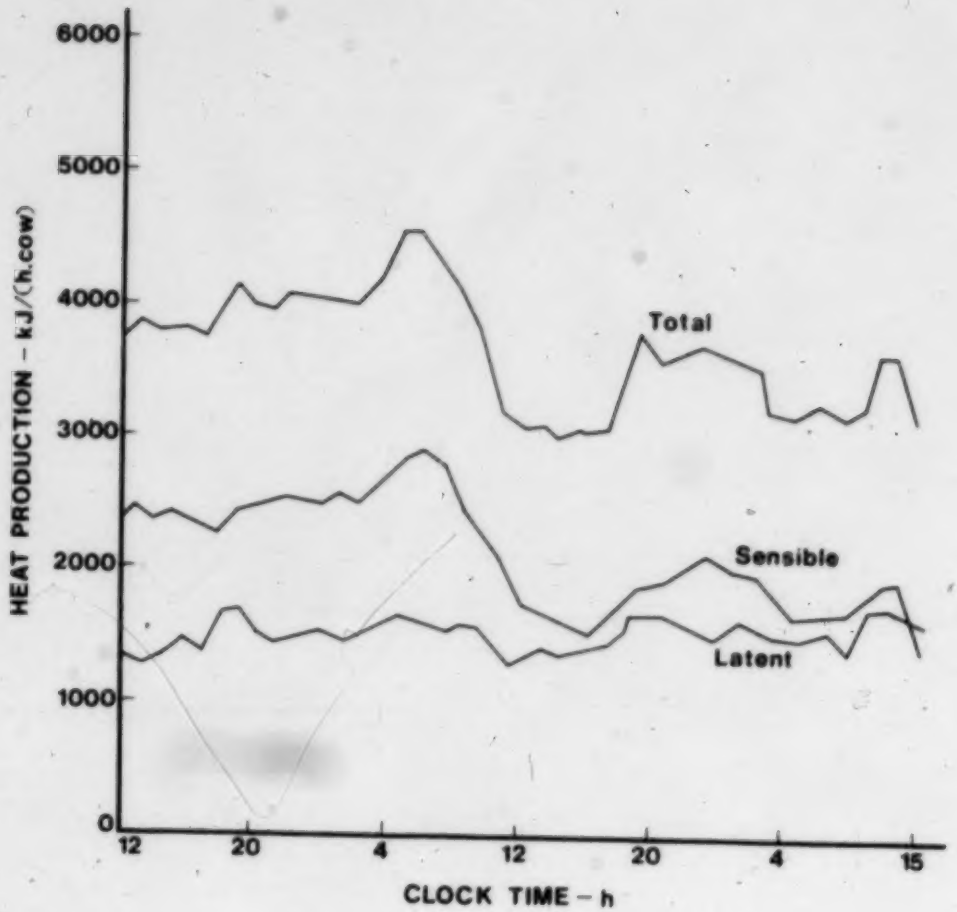


Figure 5.2 Calculated total, sensible and latent heat loads of the heat balance of Barn SL-3.

was also noted earlier, these data are used widely for design purposes. Strom and Feenstra (1980) on the other hand, in an extensive review of the literature, considered not only barn temperature in their predictions of total and latent heat outputs for dairy cows but also milk production levels and stage of pregnancy.

Total heat values predicted by Yeck and Stewart (1959), and shown in Table 5.4, were on average 3.5% lower than the values measured in this study. Smith et al. (1980) also found that total heat production was slightly lower in tie-stall than in free-stall units. The difference in activity level of cows maintained under the two systems would appear to be a logical explanation for this increase in total heat production in the free-stall operations. Of interest is the fact that the total heat values predicted by Strom and Feenstra (1980) for cows were also lower than the measured values, the average being 3.4% lower.

The difference between the measured and predicted latent heat values are striking in that the former far exceeded the maximum predicted by the previous research. On average, the measured values were 27.6 and 68.8% higher than the Yeck and Stewart, and the Strom and Feenstra predictions, respectively. The difference between measured and predicted latent heat values were more pronounced for the barns with solid passageways than for those utilizing slats. This is a reflection of the lower moisture loads associated with the latter system due to the draining of

TABLE 5.4 COMPARISION OF MEAN MEASURED HEAT PRODUCTION WITH DESIGN DATA, kJ/(h.cow (500 kg)).

Passageway	Barn			Mean Values
SOLID:	SO-1	SO-2	SO-3	
Total Heat Production;				
Measured:	4090	4458	4530	4360
Predicted:				
Yeck &Stewart(1959)	4182	4085	3890	4050
Strom &Feenstra(1980)	4330	3897	3788	4005
Sensible Heat Production;				
Measured:	2709	2686	2409	2602
Predicted:				
Yeck &Stewart(1959)	3022	2845	2489	2785
Strom &Feenstra(1980)	3400	3006	2765	3057
Latent Heat Production;				
Measured:	1381	1772	2121	1758
Predicted:				
Yeck &Stewart(1959)	1165	1238	1408	1270
Strom &Feenstra(1980)	930	891	1023	948
SLATTED:	SL-1	SL-2	SL-3	
Total Heat Production;				
Measured:	4244	4175	3341	3920
Predicted:				
Yeck &Stewart(1959)	3912	4091	3831	3945
Strom &Feenstra(1980)	4378	3504	4122	4001
Sensible Heat Production;				
Measured:	2444	2574	1943	2320
Predicted:				
Yeck &Stewart(1959)	2529	2856	2380	2588
Strom &Feenstra(1980)	3252	2726	2906	2961
Latent Heat Production;				
Measured:	1800	1601	1398	1600
Predicted:				
Yeck &Stewart(1959)	1384	1238	1457	1360
Strom &Feenstra(1980)	1126	778	1216	1040

liquids rather than their evaporation.

Further evidence of the underestimation of the 'building' latent heat component comes in comparing the measured sensible heat values with those documented in the literature. Design values, namely those of Yeck and Stewart (1959) and Strom and Feenstra (1980), were, on average, 9.3 and 22.6% higher than the sensible heat values (Table 5.4). This discrepancy may be explained by the failure of these authors to fully account for the sensible-to-latent heat shift occurring where large wet surfaces are involved as in free-stall units. Incidently, the design data were closer to the slatted barn data, thereby again reflecting the greater sensible-to-latent heat transfer that was occurring in the buildings with solid passageways as a consequence of the larger, wetter surfaces. The need for further design data pertinent to actual commercial conditions for various management and housing practices should be emphasized at this point.

The moisture removed by ventilation as latent heat in the six barns studied included that produced by the animals and that due to evaporation from wet surfaces within the building. This latter component of the moisture load involves a conversion of animal sensible heat to latent heat. This could explain the discrepancy between the measured and the predicted latent heat values of Strom and Feenstra (1980) who utilized physiological data in the derivation of their equations. The equations of Yeck and

Stewart (1959) accounted for this evaporation but not in the context of free-stall housing.

5.5 Sensible to Latent Heat Conversion

In this study, the extent of the conversion of sensible to latent heat could not be calculated directly. Because of its significance in determining moisture loads in free-stall housing, however, an estimate was made of the extent to which this was occurring in the six barns monitored. Data from the work reported by Yeck and Stewart (1959) were used to calculate the theoretical latent heat output for the cows in each unit. The percentages of the animal sensible heat converted to latent then were determined (Table 5.5). The average percentage value was 28.7 and 25.0 for the barns with solid and slatted passageways, respectively, the overall average for the six barns monitored being almost 27%.

This conversion of animal sensible heat had a marked effect on the moisture loads to be removed by ventilation from these free-stall barns. The 'building' latent heat on average accounted for 59.7 and 48.7% of the total latent heat in the units with solid and slatted passageways, respectively, (Table 5.5) the overall average for the six barns being 54.2%. These values were substantially greater than those indicated by Yeck and Stewart (1959) for their tie-stall facilities. These authors reported that, at temperatures up to 10°C, 40 to 45% of the moisture load was

TABLE 5.5 CONVERSION OF SENSIBLE TO LATENT HEAT, kJ/(h.cow (500 kg)).

Passageways	Barn			Mean Values
SOLID:	SO-1	SO-2	SO-3	
Animal Latent Heat Production, (Yeck &Stewart,1959)	614	664	851	710
Percentage of Sensible Heat Converted	22	29	35	29
'Building' Latent Heat/Total Latent	0.56	0.63	0.60	0.60
SLATTED:	SL-1	SL-2	SL-3	
Animal Latent Heat Production, (Yeck &Stewart,1959)	807	656	955	806
Percentage of Sensible Heat Converted	29	27	19	25
'Building' Latent Heat/Total Latent	0.55	0.59	0.32	0.49

attributable to evaporation from wet surfaces, with the proportion of the total latent heat directly attributable to the animal increasing as temperatures rose above 10°C.

5.6 Statistical Analysis

While six barns was deemed the minimum number necessary for this animal heat production study, it was also the maximum number that could possibly have been monitored under the scheduling circumstances at the time of monitoring. This latter fact caused some concern when it came to statistical analysis of the data as replication is of primary importance in statistical techniques. However, Steel and Torrie (1980) pointed out that the practical number of replicates for an experiment is reached when the cost of the experiment in material and time is no longer offset by an increase in information gained. With this in mind, the number of experimental units in this study was considered adequate.

As with most statistical comparisons, a number of assumptions must be made first of all regarding the experimental units. Dairy barn operations can vary enormously. Among the many variables, such factors as genetic characteristics of the herd, the nutritional value of the feed and, perhaps most importantly of all, the managements practices of each farmer were all assumed to be similar among all six barns so as to effect a valid statistical comparision.

5.6.1 Linear Correlation

The principal environmental parameter influencing animal heat and moisture production is temperature. Therefore, initial analysis of the results involved the relationship between the measured heat loads and barn ambient temperature. The SPSSX subprogram for bivariate correlation, SCATTERGRAM, was employed to measure the degree of correlation between animal heat production and the inside barn temperature. The SCATTERGRAM subprogram, in addition to giving the usual statistics associated with simple linear regressions also printed a 2-variable scatter diagram of data points. This visual aide helped in the interpretation of the extent of the linear correlation between barn total, sensible and latent heat production and the inside temperature for each of the six barns. Table 5.6 summarizes the coefficients of linear correlation for the six sets of data. Appendix E includes output from a SCATTERGRAM subprogram for a typical barn monitored.

The total heat production was not significantly dependent, at the 5% level, on the inside temperature in any barn except Barn SL-3. This is hardly surprising as the temperature range for the whole experiment was well within the zone of thermoneutrality and the animals monitiored were certainly of varying weight and production capacities. Also, as was pointed out earlier, the temperature variation in most barns monitored was narrow. Total measured heat production was subject to the dynamic thermal properties of

TABLE 5.6 SUMMARY OF CORRELATION COEFFICIENTS BETWEEN INSIDE TEMPERATURE AND HEAT PRODUCTION FOR SIX BARNS.

Passageways	Barn		
SOLID:	SO-1	SO-2	SO-3
Total Heat Production	-0.25	-0.23	-0.26
Sensible Heat Production	-0.26	-0.40	-0.68
Latent Heat Production	-0.14	+0.12	+0.32
SLATTED:	SL-1	SL-2	SL-3
Total Heat Production	-0.22	-0.11	-0.72
Sensible Heat Production	-0.50	+0.12	-0.86
Latent Heat Production	+0.26	-0.49	+0.30

Critical value of r = +/- 0.285 (Steel and Torrie, 1980)
Significance level of 5%, 46 degrees of freedom

(-) denotes a negative correlation
(+) denotes a positive correlation

the air, and thus the measurement was compounded by factors such as running motors, opening and closing of doors, and other such factors. Despite the poor correlation observed between total heat and temperature, all six barns displayed a negative correlation. Although total heat production is regarded as being constant in the thermoneutral zone and was found to be largely so in this study, this negative correlation suggests the direction of the variation between the two variables, that is, as the ambient temperature increases the total heat production tends to decrease.

The ambient temperature seemed to have the greatest influence on sensible heat production which, after all, accounted for 60% on average of the measured total heat loads. Only in Barns SO-1 and SL-2 was the sensible heat not significantly dependent, at the 5% level, on inside temperature. Again, only in two barns, Barns SO-3 and SL-3, did the temperature account for 50% or more of the variation in the heat and moisture production as measured by r^2. Also of interest was the fact that in five of the six barns, Barn SL-2 being the exception, a negative correlation existed between sensible heat production and the ambient temperature, which was as predicted in the literature.

Latent heat loads displayed a poor correlation with the prevailing temperature although, as was seen earlier, the latent heat loads in the three warmest barns were higher than in the three coolest. A positive correlation existed in four of the barns between latent heat production and the

ambient temperature. The negative correlations found in Barns SO-1 and SL-2 was probably due to the small temperature ranges and high relative humidities that prevailed in those barns (Tables 5.1A and 5.1B).

The influence of relative humidity on heat production was examined. However, this parameter had a much lesser effect on heat production than temperature. Only in two barns, Barns SO-3 and SL-2, did relative humidity account for more than 50% of any heat load. This occurred in the latent heat loads of those barns.

5.6.2 Statistical Comparision between Measured and Design Data

The Student's *t* test criterion for hypothesis testing was performed on the measured and design animal heat production data using the APL programming language. The hypothesis tested was that there was no difference between their respective total, sensible and latent heat mean values. The assumption was made that the population variances were equal. The results are reported in Table 5.7.

When testing the hypothesis at the 5% level of significance, only the measured latent heat loads of both housing systems did not agree statistically with the design data of Strom and Feenstra. In all other cases, there was no significant difference between the data being compared. Steel and Torrie (1980) have pointed out that, in the case of small-sized experiments, a null hypothesis rarely will be

TABLE 5.7 SUMMARY OF STUDENT'S t VALUES COMPARING THE DESIGN AND MEASURED HEAT PRODUCTION DATA FOR THE TWO FLOOR SYSTEMS.

Passageways	Student's t Value	
	Yeck & Stewart (1959)	Strom & Feenstra (1980)
SOLID:		
Total Heat Production	1.91 (-)	1.65 (-)
Sensible Heat Production	1.00 (-)	2.18 (++)
Latent Heat Production	2.16 (++)	3.73 (+)
SLATTED:		
Total Heat Production	0.08 (-)	0.21 (-)
Sensible Heat Production	1.12 (-)	2.60 (++)
Latent Heat Production	1.81 (-)	3.16 (+)

Student's t test on the hypothesis that the mean values of the measured and design heat production data are equal.

(-) denotes failure to reject the hypothesis
(+) rejection of hypothesis at 5% level of significance
(++) rejection of hypothesis at 10% level of significance

rejected at the 1 and 5% significance levels. Therefore, the above hypothesis was tested again at the 10% level. On this occasion, in addition to the previous rejections, a significant difference was observed between the measured sensible heat loads and those predicted by Strom and Feenstra. The latent heat loads in the barns with solid passageways proved to be significantly different to those prescribed by Yeck and Stewart (1959).

All these rejections of the hypothesis, particularly those pertaining to latent heat loads, are inherently strong statements. The earlier supposition that free-stall latent heat loads are grossly underestimated in the data from the literature is partially confirmed from a statistical viewpoint.

5.6.3 Multiple Comparision of Measured Means

The multiple comparision procedure, *Duncan's multiple range test*, which is based on standard errors, was performed on the means of the measured total, sensible and latent heat data from each barn. The results are summarized in Table 5.8. All confidence testing was at the 5% level.

With respect to analysis of the statistical comparisions of Table 5.8, any two or more means underscored by the same line indicate no significant differences between those means. Among the more noteworthy results is the agreement between the total heat production means of all six barns, the previously discussed Barn SL-3 being a notable exception to this agreement. The means of the latent heat

TABLE 5.8 SUMMARY OF RESULTS FROM DUNCAN'S MULTIPLE RANGE TEST ON THE MEANS OF THE MEASURED DATA.

Barn SO-1 = 1, SO-2 = 2, SO-3 = 3 Barn SL-1 = 4, SL-2 = 5, SL-3 = 6

	Duncan Package	Standard Error
Total Heat Production;	6 1 5 4 2 3	137.02
Sensible Heat Production;		
Solid Passageways:	3 2 1	115.06
Slatted Passageways:	6 4 5	73.18
Latent Heat Production;		
Solid Passageways:	1 2 3	87.47
Slatted Passageways:	6 5 4	36.56

production in the separate analysis of the three solid and three slatted-floor barns displayed significant differences. The corresponding sensible heat production means displayed less variability. Such statistical conclusions may indicate the greater influence of the thermal environment on barn latent heat production than on sensible heat production.

5.6.4 Comparision of Heat Loads in Barns with Solid and Slatted Passageways

In this study, the average ambient temperature of the six barns ranged from 4.2°C to 15.4°C. In analysing the data for the two manure handling systems, a comparision of heat loads adjusted for inside temperature variation would be more meaningful than comparision among unadjusted heat loads. Therefore, the question arises as to what extent the observed variation in heat production of the six barns could be attributable to the variation in inside temperature under which the data were collected? To answer this question, the heat production values needed to be adjusted to best estimates of what they would have been had all the barns been monitored at the same temperature. In an effort to remove this variation in the data due to temperature, a homogeneity of regression, modelled by Gujarti (1970) and available as an APL package at the University of Alberta Computing Services Centre, was utilized. This statistical comparision essentially checks whether or not two regression lines have the same slope. The regression lines of total, sensible and latent heat loads for both manure handling

systems, based on a common dependent variable, namely temperature, were compared.

Table 5.9 summarizes the results of this comparision. At the 5% level of significance, there was no significant difference between the slopes of the three sets of regression lines. Tests at the 10% level yielded similar results. However, at the 20% level of significance, a significant difference occurred between the slopes of both latent heat regression equations. This result points to where the greatest difference lies between the heat production of the two manure handling systems. At the 30% level, the total heat regression equations also yielded a significant difference.

TABLE 5.9 SUMMARY OF STUDENT'S t VALUES COMPARING THE MEASURED HEAT PRODUCTION DATA FOR BOTH FLOOR SYSTEMS.

Parameter	Student's t Value
Total Heat Production	1.45 (-,++)
Sensible Heat Production	0.84 (-)
Latent Heat Production	1.96 (-,+)

Student's t test on the hypothesis that the slopes of the regression lines of the measured heat production against temperature for both barn types, are equal.
(2 degrees of freedom).

(-) denotes failure to reject the hypothesis at 5% level
(+) rejection of hypothesis at 20% level
(++) rejection of hypothesis at 30% level

6. Conclusions

Based on the results of this study, the following conclusions were drawn.

1. Total heat output in the free-stall dairy barns was on average 3.5% higher than design values reported in the literature, and varied from 3341 to 4458 kJ/(h.cow (500 kg)).
2. Latent heat loads exceeded design values by an average of 27.6%, and ranged from 1381 to 2121 kJ/(h.cow (500 kg)).
3. The average latent heat loads in the units with solid passageways exceeded those with slatted passageways by 10%, the values ranging from an average of 1758 kJ/(h.cow (500 kg)) in the former to 1600 kJ/(h.cow (500 kg)) in the latter.
4. The ratio of latent heat to total heat in the exhaust air from the barns was approximately 0.40, ranging from 0.34 to 0.47.
5. An average of 27% of animal sensible heat output was converted to the latent form by evaporation of moisture within the six barns. The average conversion in units with solid passageways was 28.7% and with slatted passageways 25.0%, at average barn temperatures of 8.4°C and 11.9°C, respectively.
6. The temperature at which a free-stall barn is operated in practice would seem to have an influence on latent heat loads comparable to the manure handling system.

7. The greatest statistical differences between the measured and design data from the literature occurred in barn latent heat production.
8. Statistically, the greatest difference between the heat production of barns with solid and slatted passageways was in their latent heat component.

7. Recommendations

The results of this study indicate that manure handling systems play a significant role in dairy barn heat and moisture production. Therefore, designers of ventilation systems for dairy livestock structures should note such influences in heat balance calculations. In particular, the increased moisture loads in units with solid passageways over those with slatted passageways should be taken into consideration.

This study also revealed that, aside from the influence of manure handling systems, the design data available to Canadian producers with free-stall barns underestimates the moisture loads in those barns. Therefore, the validity of such design data, particularly with respect to dairy housing type, should be questioned.

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9. Appendix A - Processing Equations

The following equations were used in the conversion of raw voltage data to real units.

1. Thermistor-based Measurements:

a. Thermistor constant-current circuit;

$$R = E/I - L(RES)$$

where R = resistance of sensor, ohms

E = output to data logger, volts

I = constant current of 0.5 mA

L = length of thermistor lead wire, m, and

RES = resistance of wire per 30.5-m-length

b. Temperature determination from resistance;

$$1/T = AX^3 + BX + C$$

where T = temperature, °C

X = ln R

A = regression coefficient, $.209099055/10^4$

B = regression coefficient, $.275851225/10^3$

C = regression coefficient, $.137958851/10^3$

2. Dewpoint Measurement:

Dewpoint determination - (dewpoint hygrometer);

$$DP = 1.36E - 28.6$$

where DP = dewpoint, °C

E = output to data logger, volts

AA = regression coefficient, 1.36, and

BB = regression coefficient, 28.6

10. Appendix B - Error Analysis

An error analysis was performed on the primary measurements made by the data acquisition system that were necessary to perform a dairy barn heat and moisture balance.

1. Dry-Bulb Temperature Measurement;

   a. Accuracy of curved-matched thermistors,

      UUB 31J1 - 1000 ohms at 25°C,

      = +/- 0.2°C, (0-70°C).

   b. Error associated with thermistor constant-current circuit resistance and that of the thermistor lead wire = 2.23%.

   c. The resulting error associated with thermistor regression equation relating temperature and resistance = +/- 0.4°C.

2. Dewpoint Measurement;

   Accuracy of dewpoint measurement, +/- 1°C.

11. Appendix C - Heat and Moisture Balance Equations

1. Ventilation Rate;

$$Q = V A$$

where Q = ventiation rate, m^3/s

V = air speed through fan ducting, m/s, and

A = duct area, m^2

2. Psychrometric Equations;

```
p = (10**(10.79586(1.0-TT)+5.02828ALOG(TT)+
    1.50474E-4(1.0-10**(-8.29692((1.0/TT)-1.0)))
    +0.42873E-3(10**(4.76955(1.0-TT))
    -2.219598)(760)
W = 0.622 P/(B-P)
H = T + W(2501+1.86T)
SV = 2.16(T+273.16)/(B-W(B)/(0.622+W))
WS = 0.622 PS/(B-PS)
RH = (100W/WS)/(1.0-((1.0-W/WS)(PS/B)
```

where P = vapour pressure, mm Hg

W = humidity ratio, kg moisture/kg dry air

B = barometric pressure, mm Hg

H = enthalpy, kJ/kg dry air

SV = specific volume, m^3/kg dry air

WS = saturation humidity ratio, kg moisture/kg dry air

PS = vapour pressure of saturated air,

mm Hg, and

RH = relative humidity, %

3. Building Energy Losses through Ventilation System;

$$THL = V(HI - HO)/SV$$

$$LHL = V(WI - WO)/SV$$

$$SHL = THL - LHL$$

where THL = total heat loss, kJ/h

LHL = latent heat loss, kJ/h

SHL = sensible heat loss, kJ/h

HI, HO = respective inside and outside enthalpies kJ/kg dry air, and

WI, WO = respective inside and outside humidity ratios, kg/kg dry air

12. Appendix D - Regression Analysis Relating Heat Production to Temperature

Based on the analysis of the measured free-stall dairy barn heat production data, the following linear regression equations were deemed the most applicable for design purposes.

y = heat or moisture production, kJ/(h.cow (500 kg)), and

t = barn temperature, °C

TOTAL HEAT PRODUCTION IN FREE-STALL DAIRY BARNS

$y = 4482.4 - 3.77t$ $\quad r^2 = 0.6$

SOLID PASSAGEWAY FREE-STALL BARNS

Sensible Heat Production:

$y = 2888.3 - 34.0t$ $\quad r^2 = 0.93$

Latent Heat Production:

$y = 1115.0 + 76.2t$ $\quad r^2 = 0.95$

SLATTED PASSAGEWAY FREE-STALL BARNS

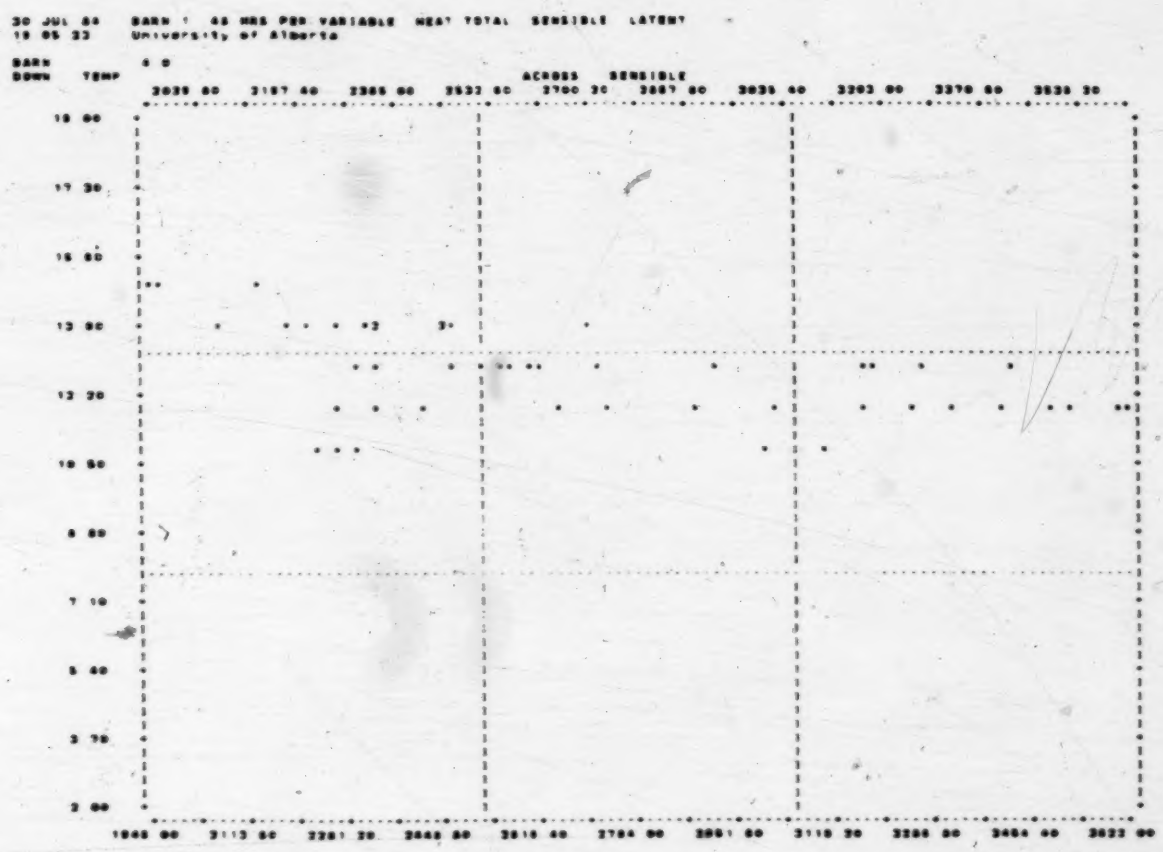
Sensible Heat Production:

$y = 31193 - 67.3t$ $\quad r^2 = 0.74$

Latent Heat Production:

$y = 1774.8 - 14.8t$ $\quad r^2 = 0.1$

13. Appendix E - Sample SCATTERGRAM Subprogram Output



30 JUL 84 BARN 1 48 HRS PER VARIABLE HEAT TOTAL SENSIBLE LATENT PAGE 34
19 05 33 University of Alberta
STATISTICS
CORRELATION (R) .69483 R SQUARED .36405 SIGNIFICANCE .00017
STD ERR OF EST .88443 INTERCEPT (A) 19.80377 SLOPE (B) .00114
PLOTTED VALUES 48 EXCLUDED VALUES 0 MISSING VALUES 0
'********' IS PRINTED IF A COEFFICIENT CANNOT BE COMPUTED